Risk influence frameworks for activity-related risk analysis during operation: a literature review

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Abstract

Experience gained in the petroleum activities have showed that major accident risk is inherent in daily activities. Risk influence methodology is perceived as a good candidate to model the activity-related risk, as a key input to operational planning decisions. The paper reviews and summarizes 11 risk influence frameworks that integrate organizational and human factors in a structured way. The intention was to evaluate how these frameworks and identified risk influencing factors (RIFs) can be used for activity-related risk analysis. The main conclusion is that it is not necessary to model explicitly RIFs for activity consequence risk - the effect that performing an activity will have on the risk level after the activity has been completed. Operational management RIFs, direct organizational RIFs, personal risk influencing factors, task characteristics RIFs, technical system RIFs, and environmental RIFs are relevant for activity performance risk - the risk associated with performing the action. Operational management RIFs influence planning, which is important to identification of interactions while estimating period risk – the risk for a plant or facility over a period.

1. Introduction

Risk analysis to support operational decision-making has become increasingly important for the Norwegian oil and gas industry as the industry has matured and more and more installations are in operation. Several aspects of operational decision-making creates a need for different risk analyses compared to the traditional QRAs[1] which are developed more for design purposes.

An important aspect is that in operation, the technical systems represents a "baseline" risk level, while experience gained in the petroleum activities have shown that the risk inherent in the activities changes more or less continuously (PSAN, 2015). The changes in risk from day-to-day are primarily activity driven, implying that an activity-based risk analysis rather than a system-based analysis is required (Haugen and Vinnem, 2015). When we are considering the risk associated with an operation on a daily basis, we need to consider different aspects of risk that consider human intervention with machines and the environment, which are activity consequence risk (ACR), activity performance risk (APR) and period risk (PR) (Yang and Haugen, 2015). This implies that human and organizational factors (HOFs) become more important to model properly. Modelling of HOFs have received great attention over the last decades. Bley et al. (1992) stated that "*any model that fails to examine the organizational factors is guaranteed to underestimate the overall risk by an undetermined amount*".

Risk influence analysis methodology focuses on identification and modelling of risk influencing factors (RIFs), as a means to efficiently identify risk reduction measures, so that a set of actions can be taken to change the state of RIFs in turn to reduce risk level (Rosness, 1998). This has gained popularity due to the inability of traditional QRA to incorporate organizational factors very well into the risk models. The methodology enables reflecting effects of "soft" factors on the performance of technical systems and human actions. Risk influence methodology is perceived as a good candidate to model activity-related risks as described above, to support operational planning decisions (OPDs) which have been identified as one of the key contributors to major accident or incidents that have major accident potential (Sarshar et al., 2015). Operational planning decisions are decisions made during the planning and preparation for execution of activities, as opposed to decisions made during the execution. For OPDs, the time lag from the need to make a decision arises until the decision is made is relatively short (Yang and Haugen, 2016). Risk influence methodology aids decision-making by:

a) Providing decision-maker (e.g., operational manager) with an overview of factors that influence the activity-related risk.
b) Providing support to identify and assess proactive risk reduction measures before activities are executed.

The overarching objective of this paper is to undertake a review of major risk influencing models that integrate organizational and human factors, to evaluate how they can be of potential use to model HOF aspects of ACR, APR and PR.

The objective is broken into the following sub-objectives:

1. Identify what risk factors can be used/relevant for activity modelling
2. Identify how risk factors can be linked to derive corresponding risk level

Eight models have been identified with keyword "risk influence" and "major accident" from published articles. The models are MACHINE (Model of Accident Causation using Hierarchical Influence Network) (Embrey, 1992), SAM (System Action Management) (Paté-Cornell and Murphy, 1996), ω-factor model (Mosleh et al., 1997; Mosleh and Goldfeiz, 1999), I-RISK (Integrated Risk) (Papazoglou et al., 2002), ORIM (Organizational Risk Influence Model) model (Øien, 2001a, b), BORA (Barrier and Organizational Risk Analysis) (Aven et al., 2006), HCL (Hybrid Causal Logic), which has been applied to oil and gas industry by Røed et al. (2009), RISK_OMT (Vinnem et al., 2012), SoTeRiA (Social-Technical Risk Analysis) (Mohaghegh et al., 2009; Mohaghegh and Mosleh, 2009) and Phoenix (Ekanem et al., 2016). In addition, WPAM (Work Process Analysis Model) (Davoudian et al., 1994) has also been included due to its activity-oriented nature. A time series of these models has been drawn in Figure 1.

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[1] QRA is short for Quantitative Risk Analysis with principles and guidelines described in ISO (2009). *ISO 31000:2009: Risk Management - Principles and Guidelines*. International Standardization Organization, Geneva, Switzerland. Different notions are used in the literature, such as Probability Safety Analysis (PSA) and Probability Risk Analysis (PRA). QRA is the unified term used in this paper.

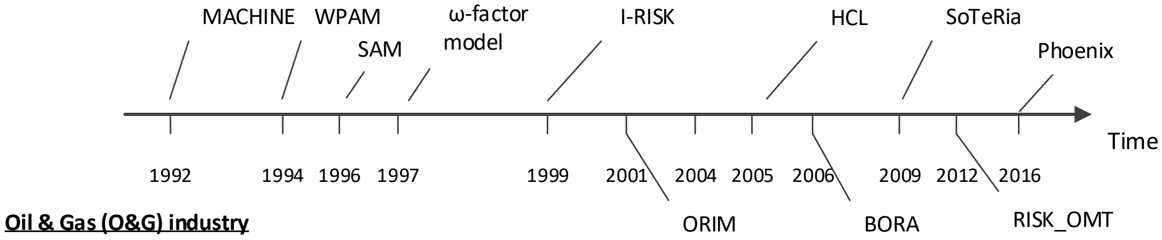


Figure 1 Time series of reviewed risk influence models

All these frameworks have the same motivation to model indirect effects of organizational factors into the risk picture. Some of the models have common parts (Skogdalen and Vinnem, 2011), such as

- A set of organizational factors
- A link to the system risk model
- A set of modeling techniques
- A set of measurement methods.

The review focuses on the different aspects of these models, from both a qualitative and quantitative point of view. The paper is organized as follows: in section 2, terminology used in risk influence modeling covering risk, risk influencing factor, risk indicator, and Bayesian network are presented. The reviewed models are compared and discussed in detail in section 3. Implications for activity-related risk analysis are discussed in section 4, and conclusion and further work are given in section 5.

2. Terminology in risk influence modelling

Risk influence methodology was developed to help stakeholders concentrate on identification and analysis of "soft" factors that may affect the risk level. These factors are called risk influencing factors which are understood as "*a set of conditions which influence the level of specified risks related to a given activity or system*" (Rosness, 1998). A "condition" refers to a relative stable property of the system or its environment (Hokstad et al., 2001; Rosness, 1998). RIFs that influence human performance and human error probability in human reliability analysis are also termed as performance shaping factor (PSFs) (Swain and Guttmann, 1983) or performance influencing factors (PIFs) (NASA, 2011). In the rest of the paper, PSFs, PIFs and RIFs are used as synonyms, and the terms that are used in the original reviewed papers are kept as they are used there. Risk indicator, as a measurable representation of the RIF, was introduced as an operational variable of theoretical RIFs. One RIF can be represented by one or several risk indicators. The risk indicators are used to assess risk on a quantitative perspective. Some examples can be the proportion of relevant people who received job safety analysis (JSA) training, proportion of relevant people who have performed JSA last year, number of JSA carried out last quarter of the year, number of controls of JSA preparation and application (Øien, 2001a).

In reviewed models, RIFs are constructed in an influence diagram or a Bayesian network diagram, which are modelling techniques that illustrate the causal relationships among factors and their influence to the risk level (Rausand, 2011). Bayesian network and influence diagram are differentiated in some literature, with the latter being used when decision nodes and utility nodes are included in the network. In reviewed frameworks, they are used interchangeably. Bayesian networks have been used in the field of risk analysis for reasoning under uncertainty based on a probabilistic inference technique. The readers are referred to Charniak (1991) and Kjaerulff and Madsen (2008) for detailed introduction.

3. Model Review

The first part of the review focuses on qualitative aspects of the different models, including what are the RIFs, sources of RIFs, levels of RIF structure, link to risk models and modeling technique. These elements demonstrate how organizational performance and human performance interface with risk influence models. The second part of the review focuses on the quantitative aspects of the models, investigating how HOFs are factored into risk estimates, by looking into how RIFs are rated, weighted, and propagated.

3.1 Qualitative aspects

The following table (Table 1) summarizes a set of qualitative aspects of the different models that have been reviewed.

Table 1 Comparison of qualitative aspects of models

Framework	Industry	Source of RIFs	Levels of RIF Structure (Bottom-up)	Link to risk models	Modeling technique
MACHINE	General	Developed from Accident data	2 levels RIFs Policy deficiency → error inducing factor → human error and hardware failure (Direct causes)	Integrate RIFs to P(Human error) and P(human induced hardware failures) to QRA (No quantification)	Influence diagram (Many to many)
WPAM	Nuclear	Used predefined set of factors from NRC (accident data)	2 level RIF Culture organizational factors (OFs) →OFs → Task → Candidate Parameter Groups → Minimum Cut Set (MCS)	Recalculation of frequency of MCS	Diagram that relate work processes and OFs
SAM	General	Statistics, expert opinion, and physical models	2 levels RIFs Management & organization factors → decision and actions → basic events (failure of physical system)	Individual decision and actions to PSAs	Influence diagram (Many to many)
ω-factor	Nuclear	Represent an organization by a model not just a set of factors	A path considering both structural and behavioral attributes of the org. Management → Manager → personnel → program → attributes → component failure rate/operator error	Relate organizational performance to equipment unavailability and operator error, to PSA	Influence diagram
I-RISK	Chemical	Safety management system (SMS)	Performance of delivery systems → technical parameter and/or human errors	Link SMS (8 delivery systems) to technical parameter and/or human errors to update QRA	Sum of product
ORIM	O&G	Leak events data sources Accident and incident report system	1 level RIF OFs → main functions performed by front-line → component/equipment → Leak frequency	Leak frequency parameter in QRA	Bayesian networks Regression based technique
BORA	O&G	Accident investigation, I-risk, WPAM, HRA	1 level RIFs Human factor + organizational factor + operational factor + technical factors → Initiating events and barrier performance	Effect of plant specific conditions on initiating events and barrier performance to update QRA	Influence diagram
RISK_OMT	O&G	OTS project and theoretical model	2 levels RIFs Indirect RIFs (Management) → direct RIFs to human failures (violations, mistakes, slips and lapses)	Update failure probability of basic event in fault trees and event trees	Bayesian networks
HCL	O&G	BORA	Full Bayesian network	Same as BORA	Bayesian networks
SoTeRiA	General	Organization performance and human safety performance theories	Cross-level Contextual factors → Safety culture → safety structure and practices → safety climate → individual-level PSF → Violation and error → unit Process model → Group safety performance (Safety critical task) → System failure rate due to OFs	Include both system failure rate due to OFs and human errors into QRA	Bayesian networks
Phoenix	General	HRA theories	3 level PIFs PIFs → Human response model → crew response tree(decision/action points) → Human failure event in PRA model	Human failure event parameter in PSA	A combination of Bayesian network, fault tree and crew response tree

3.1.1 Industry and source of RIFs

The sources of RIFs of the frameworks can be divided into four categories: accident/ incident databases, Safety Management System (SMS) and reporting systems, organization theories, and predefined sets of factors from previous work. SAM, SoTeRiA and Phoenix are rather generic frameworks. MACHINE is a generic model that has been applied to analyse railway accidents. WPAM and ω-factor are developed from nuclear industry where impact of human errors on system risk have been widely recognized. The line of research from ORIM, BORA, to RISK_OMT has been focusing on oil and gas industry, where increased engagement has been into impact of human factors on major accident causation. However, they have potential to be used across other industries as well.

3.1.2 RIFs from different models

It is no surprise that the identified set of factors between reviewed models is rather different, since the classification schemes and sources are different (Øien, 2001a). Different analysts may identify different RIFs and causal relationships from different sources. This is an inevitable challenge in general risk analysis since we are talking about "soft" factors that may be defined and organized in different ways. The detailed RIFs from reviewed models are listed in Table 2, with classification schemes and hierarchical structure indicated if there is any.

MACHINE classifies RIFs into error-inducing factors that lead to human errors and human induced hardware failures, and policy deficiencies that cause the inducing factors.

WPAM uses a predefined set of organizational factors developed for the Nuclear Regulatory Commission (NRC) (Jacobs and Haber, 1994), that might impact the safe performance of each task in a corrective maintenance work process in Nuclear Power Plant (NPP) (i.e., initiation, prioritization, planning, scheduling/coordination, execution, return to normal line-up and documentation).

SAM uses human decisions and actions as an intermediate variable between organization and system performance. No generic RIFs are recommended under the framework.

The ω-factor model proposes to consider influence from both structural and behavioural aspects of an organization. What is considered is actually a path that influence the component failure rates and/or human errors, instead of a set of factors. For example, the site manager may influence training department and quality assurance department, which may in turn influence the supervisor, the worker, and the component at the end. For human error probability, PSFs are divided into two categories: Internal PSFs (e.g., skills, motivations, and expectations) and external PSFs that strongly relate to organization (e.g., quality of procedures, operator training). This classification has clear benefits when the worker is considered an important factor in execution of the activities.

I-RISK quantifies the effect of the SMS of a plant on the risk via 8 “delivery systems” which supply the controls and resources to primary business functions (i.e., operational, emergency operations, inspection and testing, maintenance, and modifications). Among them, three are concerned directly with personnel, two with hardware, and three with how the organization works. The eight generic delivery systems are defined as: availability of personnel, commitment and motivation to carry out the work safely, internal communication and coordination of personnel, competence of personnel, resolution of conflicting pressures and demands antagonistic to safety, plant interface, plans and procedures, and delivery of correct spares for repair.The overall influence of delivery systems on a technical risk parameter (e.g., failure rate, duration of repair, probability of committing an error during maintenance) is quantified.

ORIM has been developed with focus on only one specific risk parameter - leak frequency. The RIFs included in the models are only those that may influence the leak frequency. The factors are mainly derived from causal analysis of previous leak events, and are divided into three subsets. Individual factors cover reasons for slips and lapses; operational management factors constitute the preparation/support function for front-line personnel. The third subset is for onshore management on offshore installations. The influence of organizational factors pass through layers of main functions performed by front-line personnel (i.e., process operation, corrective maintenance, preventive maintenance, well operation), and component/equipment (i.e., instrumentation including piping, pipeline, flange/joint, valve, other) to the leak frequency.

BORA integrates human, operational, organizational and technical factors into performance of safety barriers that are introduced to prevent hydrocarbon releases. The RIFs are characterised into five categories, which are personal characteristics, task characteristics, characteristics of technical system, administrative control and organizational factors/operational philosophy. The sources of the generic RIFs are investigation methods (e.g., MTO-analysis, TRIPOD), organizational factor models (e.g., I-RISK, WPAM) and PSFs from human reliability analysis (HRA) methods (e.g., THERP, CREAM, SLIM-MAUD) and HRA database.

RISK_OMT is an extension of the BORA framework that specifically focuses on maintenance work on process equipment on offshore petroleum installations. It is pointed out that RIFs may be different for the different types of human failure (i.e., human error, violation and sabotage). The RISK_OMT model examines eight scenarios and their associated activities and proposes two generic RIFs structures (for planning and execution activities respectively). The scenarios cover human intervention introducing latent errors, and intervention causing immediate release. Failure of an activity is divided into *failure of omission* (i.e., whether or not the prescribed activity is carried out) and *failure of execution* (i.e., inadequate actions that may cause failure). Causes for omission are not further included in the model, so that the probability of omission is based on historical data.

The HCL model is described in an application paper in offshore risk analysis (Røed et al., 2009). The RIFs are selected from the BORA project, but the RIFs can be linked either to another RIF, or to a basic event in the fault tree. This is different from the RIF structure in BORA.

The SoTeRiA framework is at a rather high level of abstraction, focusing on the main constructs that need to be captured to reflect organizational influence in system risk models through individual level PSFs, to unit process model, and safety critical tasks.

The Phoenix model is a qualitative analysis framework that has PIFs as the bottom layer to influence human performance model. The PIFs are developed from several HRA theoretical sources (e.g., SPAR-H, CREAM, HEART, THERP), US NRC's good practice for HRA, related database, etc. They are grouped according to their impact on operating crew behaviour. The factors are classified into three levels within nine groups. Identified PIFs are a mix of personal PIFs (e.g., knowledge, attention, stress, etc.) and organizational PIFs (e.g., safety culture, Human System Interface, resource, etc.).

Table 2 RIFs and structure of reviewed models

Framework	**RIFs**					
MACHINE	*Level 2 RIFs (Policy deficiency) → Influence to level 1 RIFs*					
	Operational feedback	Human resource management	Risk management	Design	Communications system	
	Level 1 RIFs (Error inducing factors) → Influence to: human errors (active, latent and recover) and hardware induced failures					
	Training	Procedures	Supervision	Definition of responsibilities	Demand/ resource matching	Production/safety trade-offs
WPAM	*Level 2 RIFs (Culture) → Influence to level 1 RIFs*					
	Organizational culture	Ownership	Safety culture	Time urgency		
	Level 1 RIFs → Influence to: Hardware failure rates, human error probability, unavailability of hardware due to maintenance and durations of test (^{D}: Decision making group; ^{C}: Communications group; ^{A}: Administrative knowledge group; ^{H}: Human resource allocation group)					
	Centralization ^{D}	Goal prioritization ^{D}	Organizational ^{D} learning	Problem ^{D} identification	Resource ^{D} allocation	External communication ^{C}
	Interdepartmental Communication ^{C}	Intradepartmental Communication ^{C}	Formalization ^{A}	Organizational knowledge ^{A}	Coordination of work ^{A}	Roles-responsibility ^{A}
	Performance evaluation ^{H}	Personnel selection ^{H}	Technical knowledge ^{H}	Training ^{H}		
SAM	No generic OFs recommended. Some examples are Personnel issues, Economic pressures, Flaws in design guidelines, Inspection & maintenance practices					
ω-factor	*Organization management level → Influence to site manager → Influence to department management level*					
	Directions	KSA (Knowledge, Skill, Ability)		MMA (Morale, Motivation, Attitude)		
	Department management level → Organizational PSFs level					
	Crew structure	Training department	Quality assurance department			
	Organizational PSFs level → Operator's performance				*Personal PSFs → Operator's performance*	
	Quality of procedure	Tools and parts	Task complexity	Time pressure	KSA	MMA
I-RISK	*Delivery systems → Influence to technical parameters (failure rate, pr. Of not performing an action, mean time between tests, etc.)* (^{P}: personnel, ^{H}: Hardware; ^{O}: organization)					
	Availability^{P}	Competence^{P}	Commitment^{P}	(Plant) Interface^{H}	Delivery of correct Spares ^{H}	Conflict resolution^{O}
	Internal communication and coordination of personnel^{O}	Procedures, output goals and plans^{O}				
ORIM	*Single level RIFs (Organizational factors) → Influence to leak frequency* (^{I}: Individual factor, ^{OM}: Operational management ^{OMO}: Operational Management for offshore)					
	Individual factor(for slips and lapses) ^{I}	Training/competence (sys. Knowledge, skills) ^{OM}	Procedures, JSA, guideline, instructions (task info.) ^{OM}	Planning, coordination, organization, control (preparation) ^{OM}	Design (physical construction and assembly) ^{OMO}	PM-program /inspection (activities and intervals) ^{OMO}

Table 1 (Continued) RIFs and structure of reviewed models

BORA	*Single level RIFs → Influence to initiating events and basic events* (^{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}	Task complexity ^{T}	Time pressure ^{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}
	Procedure ^{A}	Work permit ^{A}	Disposable work descriptions ^{A}	Programs ^{O}	Work practice ^{O}	
	Supervision ^{O}	Communication ^{O}	Acceptance criteria ^{O}	Simultaneous activities ^{O}	Management of change ^{O}	
RISK_OMT	*Level 2 RIFs → Influence on level 1 RIFs*					
	Mgmt_competence$^{P, E}$	Mgmt_information$^{P, E}$	Mgmt_gen$^{P, E}$	Mgmt_task$^{P, E}$	Mgmt_technical ^{E}	
	Level 1 RIFs → Influence to human error (mistake, violation, slips and lapses) (^{P}: Planning activities; ^{E}: execution and control activities)					
	Competence$^{P, E}$	Governing documents$^{P, E}$	Technical documentation$^{P, E}$	Communication$^{P, E}$	Time pressure$^{P, E}$	Workload$^{P, E}$
	Work motivation$^{P, E}$	Disposable work descriptions^{E}	Supervision^{E}	Design^{E}		
HCL offshore	*Not specified. Considered as the same to BORA*					
SoTeRiA*	*Contextual factors→ Influence to organizational safety culture and practices → Individual-level PSFs*					
	Industry and business environment	Social/national culture	Organizational vision, goals and strategy	Regulatory environment	Physical environment (climatic conditions)	
	Individual-level PSFs → Influence to human performance (violation and error)→ Safety critical task→ system failure rate					
	Individual value → Psychological safety climate→Motivation	Knowledge and physical ability → Ability	Time opportunity and physical opportunity → opportunity			
Phoenix	*Impact on operating crew behaviour (3 level PIFs) ^{1}: level 1, ^{2}: level 2, ^{3}: level 3*					
	Human System Interface (HSI)^{1}	Knowledge/Abilities ^{1}	Resources ^{1}	Team effectiveness ^{1}		Bias ^{1}
	-HSI input^{2} -HSI^{2}	- Knowledge/^{2} Experience/skill (content) -- Task training^{3} - Knowledge/ experience/skill (access)^{2} -- Attention^{3} - Physical abilities and readiness^{2}	-Tools^{2} -- availability^{3} -- quality^{3} -Workplace adequacy^{2}	-Communication^{2} -- quality^{3} -- availability^{3} -Team coordination^{2} -- Leadership^{3} -- Team Cohesion^{3} -- Role Awareness^{3} -- Team composition^{3} --Team training^{3}		-Morale/ motivation/attitude^{2} - Safety culture^{2} - Confidence in information^{2} - Familiarity with or recency of situation^{2} - Competing or conflicting goals^{2}
	Stress ^{1}		Task load ^{1}		Time constraint ^{1}	Procedures^{1}
	- Stress due to situation perception^{2} -- Perceived situation urgency^{3} -- Perceived situation severity^{3} - Stress due to decision^{2}		- Cognitive complexity^{2} -- Inherent cognitive complexity^{3} -- Cognitive complexity due to external factors^{3} - Execution complexity^{2} -- Inherent execution complexity^{3} -- Inherent execution complexity due to external factors^{3} - Passive information load^{2}		- Time constraint^{2}	-Procedure quality^{2} -Procedure availability^{2}

→ : Influence

3.1.3 Levels of RIF structure

The organizational model, human reliability model, and risk model constitute the major pillars of these frameworks. The organization is described by either a series of factors or a model that affect the performance of human error or system/component failures. Some of them have a single-level structure (e.g., ORIM, BORA); the others have two (e.g., RISK_OMT) or more than two levels (e.g., MACHINE, SAM) to structure direct and indirect influence on human or physical system performance.

For those who have a hierarchy in the RIF structure, the relationships between levels are different. Some adopt many-to-many relationships (e.g., MACHINE, SAM) without constraints. RISK_OMT is restricted to one-to-many relationships between parent and children, which means one child, can only have one parent. In addition, the level 2 RIFs can only affect basic events through level 1 RIFs. The reason for the restriction is to reduce the complexity of the model. This seems to be reasonable when second level RIFs are of a managerial nature, such as competence management, management of change and strategic task management.

3.1.4 Link to risk models

All frameworks aim to incorporate indirect organizational influence into QRA by modifying inputs to single events or sets of events in event trees (ET) and fault trees (FT). The link from organizational models to risk models are called interface model in this paper. The interface model aims at updating basic events in FT (e.g., HCL hybrid), or initiating event and barrier performance in ET (e.g., BORA), or a set of events (e.g., SAM, WPAM), which is called analysed object in this paper. Examples of analysed objects can be human error probability (e.g., MACHINE, BORA, RISK_OMT, Phoenix), component/physical system failure rate (e.g., SAM, ω-factor, SoTeRiA), technical parameters (e.g., I-RISK) and QRA parameters (e.g., ORIM). WPAM is special in that it modifies the frequency of minimum cut sets to include organizational dependencies among PSA parameters (e.g., failure rates, test interval, probability of failure due to test/maintenance).

3.1.5 Modeling technique

Most of the frameworks use variations of BN (e.g., RISK_OMT, HCL, SoTeRiA, and Phoenix) or influence diagrams (e.g., MACHINE, SAM, ω-factor). WPAM establishes an organizational factors matrix for corrective maintenance wok process, and evaluate the relative importance of organizational factors for each task, further to the candidate parameter groups. I-RISK incorporates the effects of a particular safety management system in terms of eight delivery systems to technical parameters. The overall influence of the delivery systems on a technical parameter is simply a sum of product. In ORIM, a regression-based technique is utilized to model the relationship between leak frequency and various factors.

3.2 Quantitative aspects

The quantitative elements in the frameworks are reviewed and summarized in Table 3. Some frameworks have a potential for quantification, but are still at relatively abstract level yet (e.g., SoTeRiA, Phoenix). Therefore, these frameworks are not considered in this section. The review covers the rating process, weighting process and propagation method. In addition, the review also looks at how interaction and common cause are treated in the models.

Table 3 Quantitative compare results between models

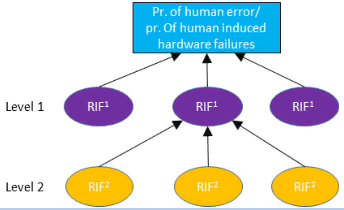
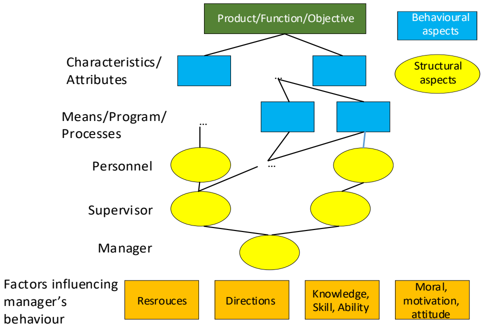
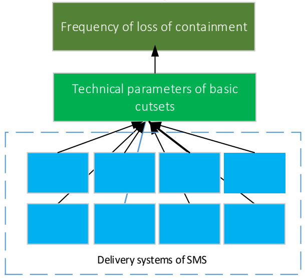
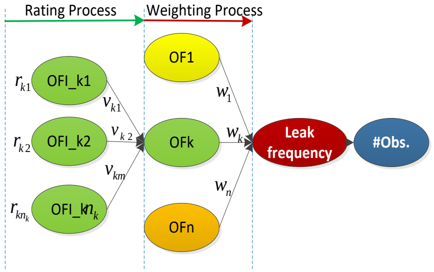
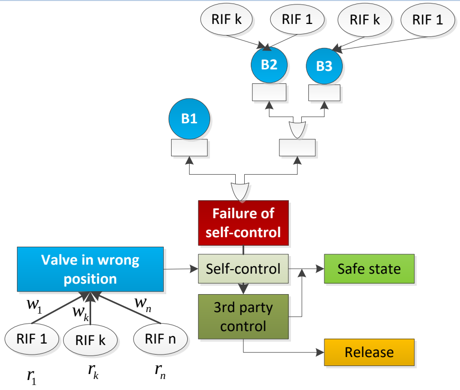
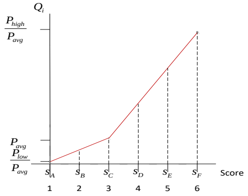
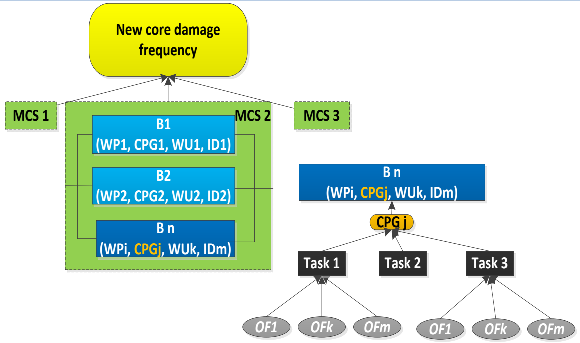
Framework	Basic model	Rating process	Weighting process	Propagation method	Interaction
MACHINE		Expert judgement to evaluate the evidence within ends of scales	Assign conditional probabilities to all combinations of states of factors (i.e., Evaluate the 'weight of evidence' of level 2 RIFs given various combination of level 1 RIFs)	Joint probability (i.e., Unconditional probability out of combination of the three first level influences)	The combined effects of RIFs are evaluated by assigning conditional probabilities to dependent RIFs
ω factor		Assume each of the nodes has binary state - event present or event absent Degree of belief as to which one of the possible states is the true state of the node	Assign conditional probabilities to all combinations of states of factors (i.e., Pr. Of a given state of the target node given the various combination of the states of the input nodes)	Update failure rate of a particular component in PSA $\omega = \frac{\lambda_o}{\lambda_I} \Rightarrow \lambda_{Total} = (\omega + 1)\lambda_I$ $\omega = \frac{\hat{p} N_{maint.}}{N_I}$ λ_{Total} : Total failure rate of a component λ_0 : rate of failure due to OFs λ_I :inherit failure rate p: Pr. of failure due to organizational causes for a maintenance operation (derived from org. model) N_I: No. of maint. operations leading to system's failure due to inherit causes $N_{maint.}$: no. of maint. Activities	Not explicitly discussed
I-risk	No risk influence diagram 	w_{ij}: expert judgement y_i: audit IRMA audit method (structured interview)	-	$m_j = \sum_{i=1}^{8} y_i w_{ij} \quad 0 \le m_j \le 10$ m_j: modification factor of the jth technical parameter y_i: quality of the ith Delivery System (DS)(i=1,…,8) w_{ij}: relative importance of jth DS on jth technical parameter $\ln f_j = \ln f_l + \frac{\ln f_u - \ln f_l}{10} m_j$ f_j: modified jth technical parameter f_u:upper value (best SMS in industry) f_l: lower value of each parameter (poorest SMS in industry)	Not explicitly discussed
ORIM		Using indicators to get assessed rating values of OFs. $r_k = \sum_{j=1}^{n_k} v_{kj} r_{kj}$ Note: convert indicator measurement to state 1 to 5	*Weight of indicators:* Expert judgment *Weighting of OFs:* Cox-proportional hazard model to get coefficients as weights (Data-driven and expert based method)	Cox-proportional model (OF vs. Leak freq.) to establish CPT $\lambda = \lambda_0 e^{\gamma_1 OF_1 + \gamma_2 OF_2 + \gamma_{12} OF_1 \cdot OF_2}$ Then use BN to update after observation $E(\lambda(t) \mid OF(t), \#Obs(t)) = \sum_{j=1}^{5} p_j \lambda_j$ $p_j = P(\lambda = \lambda_i \mid OF(t) \,\&\, Obs(t))$	Modeled in Cox model in cross terms

Table 3 (Continued) Quantitative compare results between models

Model	Basic model	Rating process	Weighting process	Propagation method	Interaction
BORA		Scores of RIFs (A-F) are from -RIF audit -TTS[2] result -RNNS[3] result Note: No attempt to use risk indicators	Expert judgment Use scale 2-4-6-8-10 to evaluate relative importance	$P_{revised}(A) = P_{average}(A)\sum_{i=1}^{n} w_i Q_i$ 	Simple approach: If two or more RIFs are assumed to be interact and worse than average, the score of ONE of them is reduced one category. If the scores are better than average, the score of one of the RIFs is increased one category
WPAM		Rating organizational factors against candidate parameter group Using BARS (Behaviorally anchored Rating Scales), surveys, behavioral checklist, structured interviews No attempt to use risk indicators	Analytic hierarchy Process (AHP) based on expert judgment	$f_{MCS} = f_{IE}\, p_1 p_{2\vert 1}; SLI_{2\vert 1} = \sum_j R_j W_j$ $W_{2\vert 1,j} = \frac{W_{1j}W_{2j}}{\sum_j W_{1j}W_{2j}}$ $\log(p_{2\vert 1}) = aSLI_{2\vert 1} + b; where$ $\log(p_2) = a\cdot(SLI_{2\vert 1} = 5) + b$ $\log(p_u) = a\cdot(SLI_{2\vert 1} = 1) + b$	NOT considered

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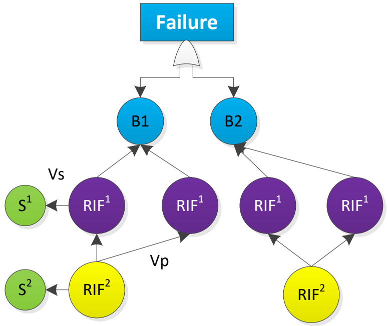
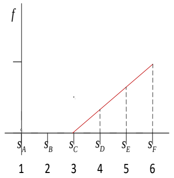
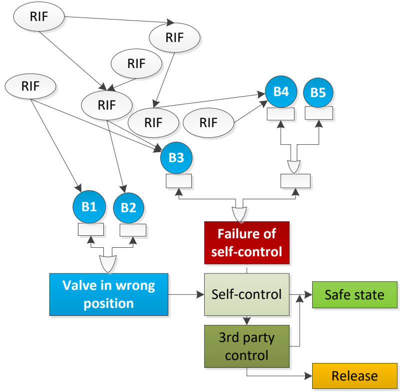
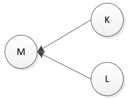
[2] TTS uses a review method to monitor and map the technical safety level on offshore platforms and land based facilities based on the status of safety critical elements and safety barriers in a context of major accident prevention Thomassen, O., Sørum, M. (2002). Mapping and Monitoring the Technical Safety Level. Society of Petroleum Engineers.

[3] RNNP project PSAN (2000). Trends in risk level in the petroleum activity (RNNP).http://www.psa.no/about-rnnp/category911.html includes a broad survey of general HSE (health, environmental, and safety) aspects, risk perception and safety culture. The surveys are conducted once every second year and they may be provided as average performance for the entire industry.

Table 3 (Continued) Quantitative compare results between models

RISK_OMT		Use score to denote the summarized information regarding the RIFs from interview, surveys, ect.	Expert judgment in Hybrid method	1. Beta distribution is used to describe parameter r in a binomial distribution with prior parameter α_0, β_0 (Jeffery's prior) 2. Update posterior based on S and V_s 3. Get prior distribution for Level 1 RIFs with parent state p 4. Update posterior based on scores of level 1 5. Get joint probability over level 1 RIFs to get q_i	w_I: Interaction effect; I is interact subset of *i* s $w_{I,i} = w_i w_I f$ $r = \sum_i w_i r_i + \sum_{i \in I} w_{I,i} r_i$ 
HCL Hybrid		Scores of RIFs (A-F), same to BORA Rate based on -TTS -Expert evaluation	*Assign weights:* 1. Determine by expert judgment the relative change in E (M), when one parent is changed from A to F, the other parent is locked to C. 2. Same procedure to the other parent. 3. Normalize the result 	*Principle for assigning CPT:* The more distant the state of child from the parents' states, the lower the probability that should be assigned *CPT for the RIFs* $Z_j = \sum_{i=1}^{n} \lvert Z_{ij} \rvert w_i Z_j \in (a,b,c,d,e,f)$ $P_j = \frac{e^{-RZ_j}}{\sum_{j=a}^{f} e^{-RZ_j}}$ *CPT for the Binary events (*Q: adjustment factor) $P_j = P_{basis} \sum_{i=1}^{n} w_i \sum_{k=a}^{f} P_{ik} \cdot Q_{ik}$	Interaction is covered in terms of CPT. Positive correlation is dealt with by adjusting the assigned states: 1. Remove absolute values of Z_j 2.Apply different Rs when it is believed to be a correlation between the parents RIFs 3. The corresponding R indices are applied for the calculations of each of the six numerators

3.2.1 Rating process

Rating of RIFs means to assess the factors and determine which state they are in on a unified scale of states (scores). There are typically three approaches proposed to assign scores of RIFs in the reviewed frameworks: 1) using a set of indicators (e.g., ORIM), 2) using RIF audit aided by e.g., BARS (Behaviorally anchored Rating Scales) using behavioral checklists, structured interviews or surveys (e.g., WPAM, BORA, HCL hybrid, RISK_OMT) or 3) expert evaluation (e.g., MACHINE). BARS allows a quantitative assessment of these factors by asking a group of respondents to read the definition of an organizational factor and descriptions for ineffective behavior (score 1) to very effective behavior (score 5) and rank their organization on the scale. The result is an average of the available scores. I-Risk uses the IRMA (Integrated Risk Management Audit) audit method, which uses structured interviews to assign ratings to the eight delivery systems on the assessment of the management activities.

Note that RISK_OMT has a different structure to model scores of RIFs as nodes in BN. The underlying perception of RIFs is different from other frameworks. In ORIM, BORA, WPAM, the RIF is assumed to be known without uncertainty. In RISK_OMT, the RIFs are assumed to have true values that we do not have exact knowledge about. Hence, the RIFs are treated as stochastic variables and the scores are observations of those true values.

3.2.2 Weighting process

Weighting of RIFs is to evaluate the importance of RIFs relative to the analysed object (e.g., basic event, safety critical task, event and MCS). MACHINE and the ω-factor model assign conditional probabilities to all the possible combinations of states of the RIFs instead of assigning weights. The overall challenge of using conditional probability tables (CPT) lies in the fact that the number of probabilities required can be substantial, something which makes the assignment process difficult to carry out in practice. Therefore, MACHINE proposes to use Success Likelihood Index Method (SLIM) (Embrey, 1986) in the weighting process; the ω-factor model suggest to use either expert judgment or a data-driven approach; HCL hybrid develops a principle to assign the CPT.

BORA and RISK_OMT use expert judgment to find the relative importance of RIFs and then normalize the weights to sum up to one. Analytic Hierarchy Process (AHP) is adopted in WPAM by asking experts to rate the OFs two at a time to evaluate their importance. The advantage of AHP is that the consistency of those judgments can be measured (Davoudian et al., 1994). I-Risk weights every delivery system according to its relative importance for each technical parameter based on expert judgement. ORIM applies a data-driven and expert based method to establish a Cox proportional hazard model to get estimated coefficients as weights. The procedure to get the coefficients is rather complicated since the state of organizational factors back to time the leak happened is unknown. A hidden Markov Model is used to estimate the former states, and the number of contributions to leaks of factor OF_k is Poisson distributed.

3.2.3 Propagation method

After the scoring and weighting process of the RIFs, the scores and weights are aggregated in order to reflect the total effect of all RIFs on the analysed object. When the framework has more than one level of factors, the effect is propagated through the framework. The two key points are: 1) what is propagated through the RIF structure, and 2) what is the relationship between risk and aggregated RIFs.

In ORIM, the risk is defined as a complete set of scenarios (Si), the likelihood (Li), and the consequences (Ci) of each scenario. The probability is interpreted as an objective probability to show the likelihood of the scenario happening. WPAM and BORA follows the same interpretation. The RIFs are assumed to be known and the effects are propagated into a true likelihood of the basic event/event/MCS. In RISK_OMT, RIFs are still considered theoretical constructs that influence the risk. Yet the probabilities are subjective probabilities that express uncertainties, which means what is propagated is our uncertainty regarding the occurrence of the basic events, instead of the true likelihood of the event occurring. In MACHINE, SAM, ω-factor and HCL frameworks, risk is not explicitly defined. Mathematically, a Bayesian probability is assigned to different combinations of states of the RIFs. The detailed processes of propagation of the models are described in Table 3.

3.2.4 Interaction between RIFs

Interaction effects among RIFs means that a RIF will have a different effect on the basic event, depending on the status of another RIF (Aven et al., 2006). RIFs are assumed to be independent while developing basic risk influence models. In practical applications, it is more reasonable to believe that interaction effects exist. And these interactive effects increase the "*difficulty of identifying and quantifying causal links between a multitude of potential causal agents and specific observed effects*" (Klinke and Renn, 2002). For those frameworks that use conditional probability tables, the interaction effects are taken into account automatically, as long as the RIFs that interact are parents to the same child. Interaction between two RIFs is considered in ORIM in terms of cross terms. BORA deals with interaction in a simple way. For example, if two or more RIFs are assumed to interact and worse than average, the score of ONE of them is reduced one category (e.g., from C to F).

RISK_OMT introduces interaction effect factor $W_{I,i}$ and summed the interaction effects for one sub set of interactions to the original weighted sum to get a conservative result. This is to address that low values of two or more RIFs strengthens the negative influence on the basic event.

4. Discussion

In this section, we will start by discussing what are included in activity-related risk analysis to support operational planning decisions. This is followed by a summary of key requirements that we need to place on the analysis methods. Next, we discuss these requirements in relation to the reviewed frameworks to evaluate their applicability to model the activity-related risk.

4.1 Activity-related risk analysis

In daily operation of an oil and gas process plant, we have to relate to different aspects of risk compared to when we are designing a plant. This obviously needs to be reflected in the analyses we are doing to capture both the short-term and long-term effect of operational planning decisions. These "risk types" as we call them are described in more detail in Yang and Haugen (2016), and we only briefly describe them here, as a basis for the following discussion.

4.1.1 Activity consequence risk (ACR)

Activity consequence risk is the effect that performing an activity will have on the risk level for the plant after the activity has been completed (Yang and Haugen, 2016). It is a reflection of influences of the analysed activity on the baseline risk level of the plant or the site-specific average risk according to the classification scheme proposed by Yang and Haugen (2015). The site-specific average risk can be viewed as the long-term average risk for a plant, based on a set of assumptions about the condition of the systems/equipment to be used on the site and the types of activities taking place. ACR is introduced to separate out the effect on the technical condition of the plant as a result of performing the activity. For example, a new pump may increase the leak frequency; the gas detection system may be upgraded to improve the performance and maintenance can be performed to improve reliability of components. As part of the decision-making about whether to perform activities or not, this is clearly relevant information. ACR intends to capture such information.

4.1.2 Activity performance risk (APR)

ACR says something about the effect on risk after we have completed an activity while Activity performance risk is the risk associated with performing the action, or the risk level during the activity (Yang and Haugen, 2016). As pointed out by Haugen and Vinnem (2015), changes in the risk level during operation is governed by the activities, with system conditions as a constraint on what can be done. Compared to ACR, which is long-term oriented, APR is temporally increased risk to the baseline risk level, which will "vanish" when the activity has been completed.

4.1.3 Period risk (PR)

Period risk is similar to APR, except that this takes into account all activities taking place during a given period at the plant (Yang and Haugen, 2016). Due to the possible dependencies between concurrent activities, PR associated with these activities will not necessarily be the sum of APRs of the activities. Technically PR can be the baseline risk/site-specific average risk if we consider a period of one year for the whole plant, but this is not the intention. We want to focus on short-term risk due to interactions of simultaneous activities, with the technical "health" condition of the facility as a constraint. Figure 2 presents the difference between PR, and APR and ACR.

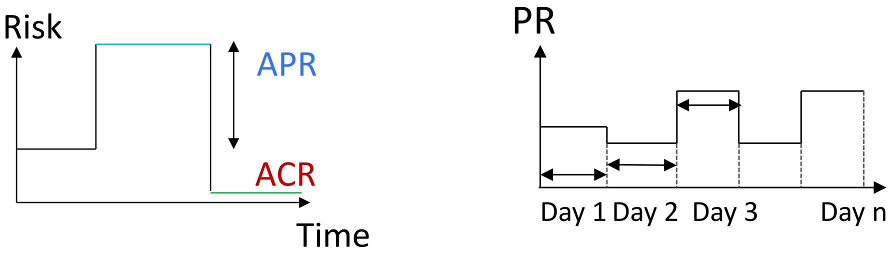


Figure 2 Illustration of ACR, APR and PR

4.2 Requirements to analysis methods for activity-related risk analysis

Based on the above descriptions of the different information required to activity-related decision-making, we can summarise key requirements to the analyses in the following table (Table 4).

Table 4 Requirements to activity-related risk analysis

	ACR	APR	PR
Takes into account	Technical health condition of plant	Safety critical parameters of activities	Interactions between activities
Key requirement	Must be able to reflect changes of status of safety critical technical systems	Must reflect activities explicitly and critical parameters (RIFs) that influence performance of activities	Must analyse activities in sufficient detail to reflect interactions among concurrent activities that influence risk
Sub-requirement	*-Safety critical technical systems (especially technical safety barriers) must be modelled* *-"Health status" of the systems should be possible to change in the models* *-Changes in "health" caused by activities should be reflected in the model*	*-Safety critical parameters should be identified for the activity* *-Status of the safety critical parameters should be possible to reflect in model* *-Operational barriers, temporary barriers, work descriptions, procedures, and operational parameters should be reflected*	*-How concurrent activities can interact that lead to hazardous events or escalate hazardous events to major accidents should be included in model*

4.3 Implications of reviewed frameworks to activity-related risk analysis

All reviewed models aim to integrate HOFs into QRA to reflect the human interaction into operational risk analysis by updating QRA parameters directly or indirectly. The parameters include, but are not limited to frequency of initiating events, equipment unavailability, probability of human errors, probability of human induced hardware failures, failure rate of a particular component, test interval of equipment, duration of repair time, and so on. Conventional QRAs for offshore installations have been focused on modelling of technical systems and layouts, with limited explicit modelling of activities. Then to what degree is QRA suitable for activity-related risk analysis?

The conventional QRA may be regarded as a system-based analysis that was developed for quantifying the risk level of the design of the plant, for prioritizing technical risk reduction measures and for comparing alternative designs. With the focus on technical systems, it may seem reasonable to assume that QRAs are suitable for modelling ACR. Unfortunately, the modelling tends to focus more on consequence-reducing measures than frequency-reducing measures. This is a weakness in daily operation when the first priority always is to avoid accidents, not to reduce the consequences should they occur. As a result, many changes in factors that influence the probability of hazardous events actually have no or little impact on QRA results (Vatn and Haugen, 2013). Moreover, QRA typically averages a range of consequences and provides risk results in terms of expected losses, which is not sensitive enough for status changes of technical safety systems. This limits the conventional QRAs to be used to reflect the changes of baseline risk level due to completion of the analysed activity. I-risk, ORIM, BORA and RISK_OMT shifted the focus from consequence of the leak to reduce the leak frequency in QRA. There are also other methods that aim to tailor the frequency of hazardous events based on evaluation of technical, operational and organizational factors, such as MANAGER (Pitblado et al., 1990), API 581 risk-based inspection guideline (API, 2000), TEC2O (Landucci and Paltrinieri, 2016) and so on. They provide good frameworks for estimation of ACR.

If we look further at APR and PR, the main problem is that conventional QRA lacks of details to reflect risk on an activity basis. Controlling APR directs more attention to frequency-reducing safety barriers rather than consequence-reducing safety barriers. Human/operational barriers (e.g., testing, supervision, self-check) are the main barrier systems and they should be reflected into estimation of APR. Moreover, in some cases, temporary barrier systems are introduced to replace temporally unavailable barrier system. These barriers are usually not explicitly reflected into the QRA, but their significance promotes them into APR and PR estimation. BORA and RISK_OMT incorporate operational barriers into QRA that enable risk influencing structure to be used for APR estimation. In addition, most daily activities are modelled only implicitly, e.g., by saying that the leak frequency only is dependent on the type and number of equipment, not the number of activities can cause leaks. Historically, activity-related leaks are also recorded in historical leak frequencies and are therefore taken into account, but it is not possible to change the risk results by changing the number of activities. This creates limitations to estimate PR, when number of simultaneous activities and their interaction matter.

To summarize, it is clear that modifying the parameters in the QRA not is sufficient to give the answers we need. This means none of the frameworks can be used directly to model ACR, APR and PR. However, the ability to model HOFs is clearly important, even if the basic models need to be modified also. Because of this, we have chosen to look further at the RIFs that are identified in the reviewed methods, and how they are linked to derive risk level.

4.3.1 Summary of RIFs from reviewed frameworks

The reviewed frameworks have a lot in common when it comes to RIFs for technical failures and human performance. Different terms are however used, and, as pointed out by Groth and Mosleh (2012), these terms are used without being defined specifically enough to ensure consistent interpretation of similar RIFs across methods. Note that we use RIF as a common term for PIFs/PSFs as well. For this purpose we will classify factors influencing technical or human condition/performance into the following groups.

- *Indirect organizational RIFs*: RIFs at organizational level that are root causes for system risk/accidents. MACHINE classifies these as policy deficiency, human resource management, risk management, design and communication system. WPAM use the terms culture level, ownership, safety culture, and time urgency. SoTeRiA applies regulatory auditing system, organization safety structure & practices, organization safety culture, and emergent process as organizational root causes. These RIFs are generally counted for through the quantification of their influence on probability of human failures, or operational management on technical failures (e.g., maintenance strategy).
- *Direct organizational RIFs*: Factors that shape worker's behavior that are strongly related to organization. Training, communication and coordination of personnel fall in this category.
- *Operational management RIFs*. Operational management is a support function that helps operators carry out work in a scheduled and structured manner. It is influenced by indirect organizational RIFs and influences both probability of technical failures and human failures during operation. The RIFs are more on the operational level, such as work practice, procedure, guideline, instructions, planning, supervision, coordination, preventive maintenance program, production/safety trade-offs, resource allocation, etc. Direct organizational RIFs and operational RIFs have some overlap with respect to the factors that influence probability of human failures at the operational level.
- *Personal RIFs/Individual level RIFs*. Personal RIFs represent the individual characteristics of the operator, such as competence, skill, knowledge, working load, fatigue, motivation and expectations, etc. Personal RIFs come largely from personal characteristics. This is classified by Mohaghegh (2007) as individual PSFs.

- *Task characteristics RIFs*. This group of RIFs covers aspects related to the activity itself, such as methodology to carry out the task, task supervision, task complexity, time pressure, availability and operability of tools, availability of spares that are needed for the activity. This group is described in detail in BORA framework.
- *Technical system RIFs*. These RIFs cover aspects related to design of equipment or system, complexity of the system, accessibility/maintainability, system feedback, and technical condition in general. This group of RIFs is also detailed discussed in BORA framework.
- *Environment RIFs*. This group of RIFs covers external environmental factors such as weather conditions. The weather conditions can affect both individuals and technical systems, as discussed in SoTeRia framework.

Indirect organizational RIFs are excluded for activity-related risk analysis, which is a support to operational planning decisions that have short time lag in between decision and action. The reasons are as follows. Firstly, these RIFs are rather stable for long periods, unless major organizational changes happen. Secondly, what we aim to manage while planning is direct contributors to technical failures and human failures, regardless of the state of the organization. Thirdly, the short time lag constricts the resources being available to capture the most remote type of organizational factors. In spite of this, it does not mean that influence of indirect organizational factors are not considered in the risk picture since they are implicit in the baseline risk level of the plant.

4.3.2 Relevant RIFs and ACR

Yang and Haugen (2016) proposed to use a combination of event tree and fault tree to model site-specific average risk, with a focus on technical failures of the system, especially barrier systems. As a result, influence of RIFs are reflected into site-specific average risk via influence on the frequency of hazardous events, failures of barrier system, and number of exposed people. Under the assumption that direct organizational RIFs are rather stable before and after the completion of the activity, the focus of ACR can be on the change of technical parameters in the model. Correspondingly, ACR is derived by updating failure rates, frequencies of hazardous event, and so forth. Operational management RIFs (e.g., maintenance program) may influence ACR indirectly by influencing technical parameters (e.g., test interval, mean time to repair). However, for specific activities, the effect is taken directly into account and we do not need to include the operational management RIFs in the model explicitly.

4.3.3 Relevant RIFs and APR

In Yang and Haugen (2016), it was suggested to control APR through monitoring of safety critical parameters, which are the factors that have direct and significant effects on the occurrence and/or consequence of hazardous events. In Figure 3, the parameters are illustrated together with possible deviations (failures) and how these can occur. While performing the activity, we shift focus from average performance of the technical system to whether relevant barrier systems are actually working or not. This means that if detection is not carried out, detection method is wrong, or execution of detection fails, APR may increase. Temporary barriers might be set up as a compensatory measure for out-of-service physical barriers. Operational barriers such as supervision and leak test may fail because of omission or failure of execution. APR increases as a result of human errors (e.g., no gas freeing, inadequate blinding or wrongly assembled flanges). APR might also increase if operators fail to recognize the working constraints (e.g., weather, restricted area, or restricted time), or fail to follow the constraints. In addition, exposure of unnecessary people while performing the activity exacerbates the consequence of major accident.

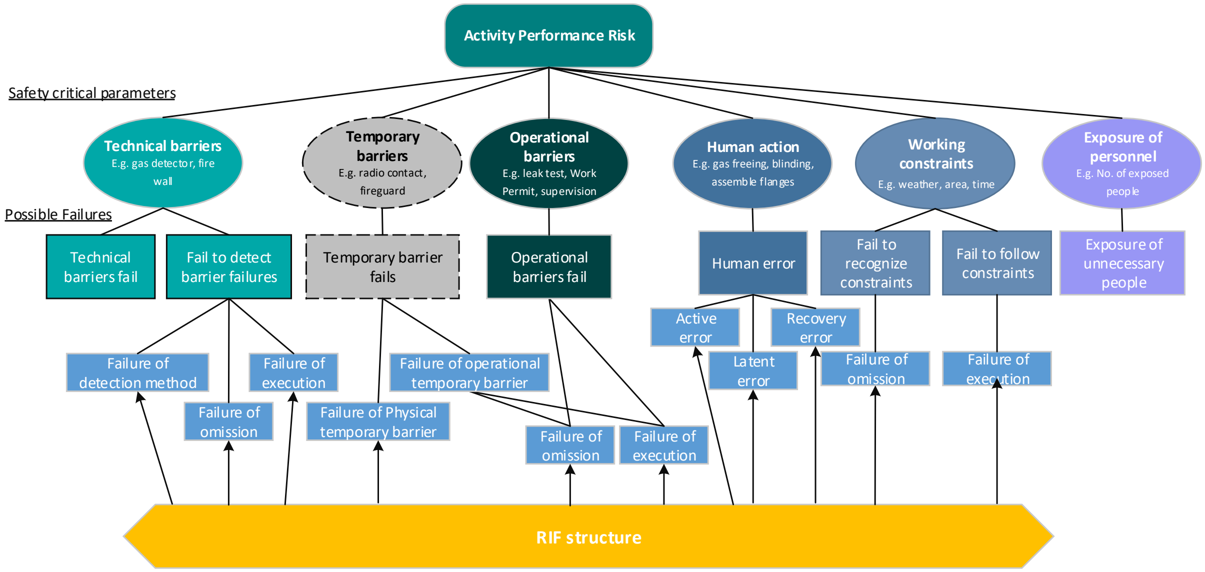


Figure 3 Safety critical parameters to APR

We limit the safety critical parameters to the factors that have direct and significant effect on APR, leaving the factors that have indirect influence to APR via influence to safety critical parameters as RIFs.

When analysing APR, conditions of technical barrier systems are highly relevant, but RIFs that influence their performance are out of consideration. What matters the most is the detection of conditions of relevant technical barrier systems to see if they are functioning, degraded or failed. So more attention is directed to performance of the operators who are responsible to detect the status of technical barriers, set up temporary barriers, carry out operational barrier functions, perform the action, recognize and follow working constraints.

Many reviewed frameworks discussed influences of RIF structure on human performance. MACHINE divides human errors into active errors, latent errors and recovery errors. Active errors have a direct impact on the safety because of the immediacy of their adverse effects. Latent errors are the ones that are left by wrongly performed activity (e.g., maintenance work may leave incorrectly fitted flanges or bolts that can later lead to a leak), and recovery errors are those that leave latent errors not detected at later stage (e.g., supervisor fails to carry out specified checks to detect the error). This classification clarifies how performing the activity - human action - can fail. Recovery errors means failure of some operational barriers such as self-check, supervision, or 3rd party control which are established to reveal latent errors.

RISK_OMT differentiates *failure of omission* and *failure of execution* (Vinnem et al., 2012). Failure of omission describes inadequate or insufficient functionality of the work - action is not carried out. Failure of execution covers “violations” and human errors which is further categorized into “mistakes” and “slips and lapses”. The human failures may lead to fail to detect barrier failures, temporary barrier failures, operational barrier failures, action failures, and work constraints failures. Note that we adopted both classification of human performance in order to clearly address different possible failure mechanisms for safety critical parameters.

MACHINE, ω-factor, BORA, RISK_OMT, and Phoenix provide a selection of RIFs that influence the probability of human failures. The selections of RIFs to different possible failures mechanisms (e.g., failure of execution, failure of omission) of safety critical parameters may be different. In general, operational management RIFs, direct organizational RIFs, personal RIFs, task characteristics RIFs, technical system RIFs, and environmental RIFs are relevant and need to be identified as a means to control APR. A detailed analysis should be conducted for specific activities.

The sources of RIFs are expected to be more site-specific and activity specific. In Norwegian oil and gas industry, besides factors from ORIM, BORA, RISK_OMT, safety management system and accident/incident reporting systems, as suggested by I-Risk, provide important areas of concerns while carrying out causal analysis.

Deciding the levels of RIF structure to safety critical parameters is a matter of how further we want to trace and control the influencing sources. To reduce the complexity of the model of APR, single-level structure as ORIM and BORA is recommended. This is under the assumptions that status of the organization is rather stable and that direct contributors to human errors are captured in the identified RIFs.

Influence diagram (or Bayesian networks) is adopted by the most reviewed frameworks and it is also considered as a good candidate for APR modelling. It provides an intuitive representation of factors that influence the safety critical parameters that influence APR at the end. It also takes interactions of the RIFs into account under conditional probability table. The evaluation requires a fast rating of the RIFs while doing short planning, so audit as suggested by I-Risk and the review method and survey used by BORA are not well suited. Expert evaluation is a feasible way to rate RIFs when operational personnel is experienced and specialized in the activity. Utilization of indicators (i.e., ORIM) or scores (i.e., RISK_OMT) enables a speedy evaluation (Øien, 2001a) that is of interest to explore further. Assigning conditional probability table is more challenging at an activity level. Using expert judgement to find the relative importance of RIFs as used in BORA is the simplest method but is constrained to subjectiveness. The data-driven approach suggested by ORIM requires a big historical data about specific activities and this is only feasible when activity-related incident/accidents and corresponding causes are well collected. The HCL hybrid approach may apply since only a few input parameters need to be assigned. It facilitates the assignment process for the activity that has short period. The propagation can be carried out using software HUGIN or Netica.

4.3.4 Relevant RIFs and PR

PR considers all the activities for the concerned period to avoid possible interactions that may lead to major accident. The key task is accordingly identification of the interactions. Yang and Haugen (2015) recommended to use bow-tie to identify possible interactions via influence of activities to the elements in the bow-tie (i.e., hazards, triggers, proactive barriers, hazardous event, reactive barriers and consequences). This raises requirement to understand how the activities will influence the system locally and globally while planning. Planning is concerning the time, location, and allocation of resources for each activity. When these aspects are not clearly defined in the plan or the plan does not exist, the interactions are difficult to foreseen. RISK_OMT proposes a generic RIFs structure to planning that mistake, violation and slips and lapses are the main error types. They are influenced by competence, governing documents, technical documentation, communication, time pressure, workload and work motivation. They are classified into operational management RIFs that influence the supporting function from the organization. The same to APR modelling, a single-level RIF structure and influence diagram are also applicable to period risk modelling. This means the rating, weighting, and propagation can be the same as well to keep modelling consistency. The relation between RIFs and PR is presented in Figure 4.

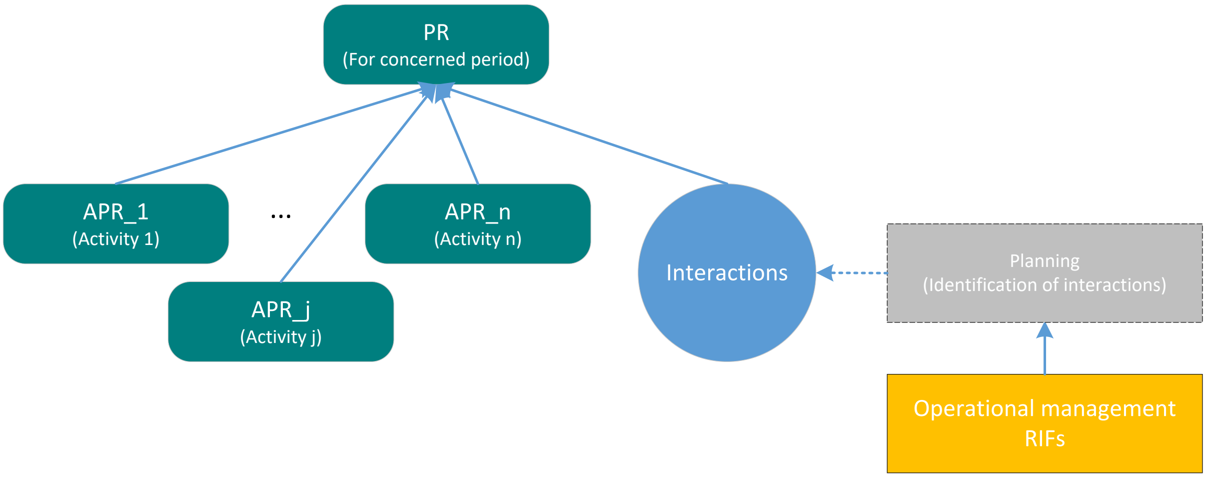


Figure 4 RIFs and Period risk

4.4 Summary of RIFs and activity risk modelling

A summarized illustration of activity-related risk and relevant RIFs, and implications from reviewed frameworks are shown in Figure 5. With a focus on concrete technical conditions of the systems, RIFs are not necessarily explicitly modelled for ACR. This also applies to technical conditions of barrier system for APR. For APR analysis, more attention is directed to human failure that can lead to failures/deviations of performance of most of the safety critical parameters. Planning is critical to identification of interactions of activities while evaluating PR, hence operational management RIFs are the RIFs that influence the performance of planning.

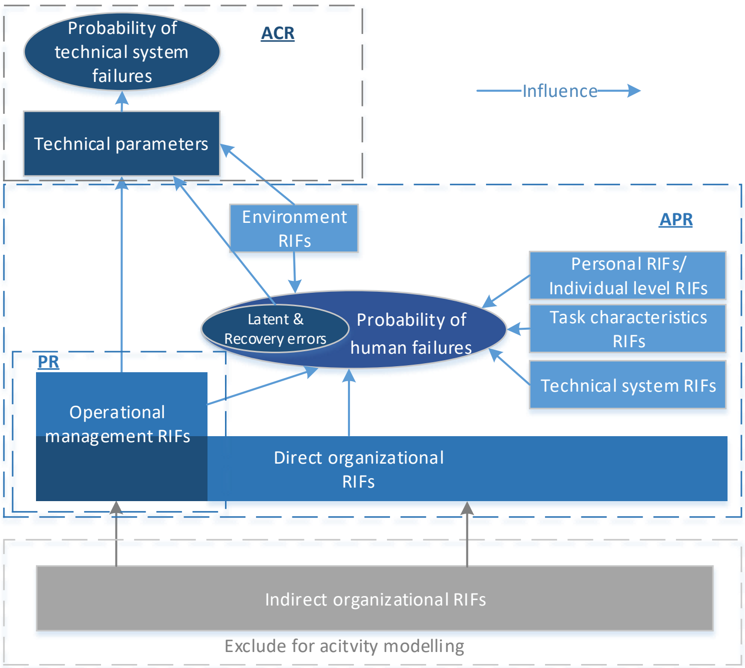


Figure 5 RIFs for activity risk analysis

There is no single framework that provides all the answers to modelling of the three aspects of risk. Table 5 summarize the implications from reviewed frameworks following the same structure as the review in Table 2 and Table 3.

Table 5 Implications from reviewed frameworks to ACR, APR and PR

	ACR	**APR**	**Reference framework**	**PR**	**Reference framework**
RIFs	RIFs are not considered	Personal RIFs/Individual level RIFs Task characteristics RIFs Technical system RIFs Environment RIFs Operational management RIFs	All frameworks	Operational management RIFs	RISK_OMT
Sources of RIFs		SMS Accident/incident reporting systems	I-RISK ORIM BORA RISK_OMT	RISK_OMT	RISK_OMT
Levels of RIF structure		One level	ORIM BORA	One level	ORIM BORA
Link to risk model		RIFs → Human error probability → safety critical parameters → APR	MACHINE, BORA, RISK_OMT, Phoenix	RIFs → planning → interactions → PR	RISK_OMT
Model technique		Influence diagram or Bayesian network	MACHINE ORIM BORA RISK_OMT ω-factor	Same to APR	
Rating		Expert evaluation Indicators Scores	ORIM RISK_OMT	Same to APR	
Weighting		Conditional probability table	HCL	Same to APR	
Propagation		Bayesian network (e.g., HUGIN, Netica)	-	Same to APR	
Interaction		Taken into account in BN	HCL	Same to APR	

5. Conclusion and further work

The objective of this paper is to give a better understanding of concepts of risk influencing modeling and to evaluate how existing frameworks can be used to model activity-related risks. A comparative study is undertaken to show differences between the frameworks from both qualitative and quantitative aspects (Table 1 and Table 3). The Risk influencing factors and corresponding structures from reviewed frameworks are summarized in Table 2, as a basis to explore what type of RIFs may be relevant for activity-related risks, which are activity consequence risk, activity performance risk, and period risk. The review has been done in a very thorough manner, to provide a clear picture of similarities and differences of the reviewed framework. One conclusion is that reviewed frameworks are mostly aiming at updating QRA that are established for the design phase in the first place. The way that QRAs currently are performed will not be able to provide most of the information for activity-related risk. However, learnings from these frameworks can be valuable to activity performance risk, which is the risk associated with performing the action, and period risk, which captures risk over a concerned period. The influence of RIFs to activity performance risk is via human performance that are essential to some of the safety critical parameters. Operational management RIFs are essential to performance of planning, which is critical to identification of interactions while evaluating period risk. In conclusion, we found that risk influence methodology with risk indicators might be a good alternative to model and estimate activity performance risk and period risk with limitations. This will be the next step of the research, which will focus more on quantification of activity performance risk and period risk via operational risk indicators.

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Appendix A

ACR	Activity Consequence Risk
AHP	Analytic hierarchy Process
APR	Activity Performance Risk
ALARP	As Low As Reasonably Practicable
BARS	Behaviourally anchored Rating Scales
BN	Bayesian Network
BORA	Barrier and Operational Risk Analysis
CPG	Candidate Parameter Group
CPT	Conditional Probability Tables
ET	Event Tree
FT	Fault Tree
JSA	Job Safety Analysis
HCL	Hybrid Causal Logic
HOF	Human and Organizational Factor
HRA	Human Reliability Analysis
ID	System Identification
I-RISK	Integrated Risk
IRMA	Integrated Risk Management Audit
OF	Organizational Factor
O&G	Oil and Gas
OPD	Operational Planning Decision
ORIM	Organizational Risk Influence Model
PR	Period Risk
PRA	Probabilistic Risk Analysis
PSA	Probabilistic Safety Analysis
PIF	Performance Influencing Factor
PSF	Performance Shaping Factor

SLIM	Success Likelihood Index Method
WP	Work Process
WU	Working Unit
MCS	Minimum Cut Set
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
O&G	Oil and Gas
QRA	Quantitative Risk Assessment
RF	Risk Factor
RIF	Risk Influencing Factor
RISK_OMT	Risk modelling – integration of organisational, human and technical factors
SAM	System Action Management
SCP	Safety Critical Parameters
SMS	Safety Management System
TTS	Technical Condition Safety

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