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Dynamic Evaluation of Risk: from Safety Indicators to Proactive Techniques

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This contribution presents a short review of dynamic risk evaluation techniques based on human and organizational factors, from the first approaches developing indicators to the aggregation methodologies integrating risk analysis. A methodology for the evaluation and update of expected release frequencies is taken as example of last generation techniques. The methodology aiming to support dynamic risk assessment studies is named TEC2O – Frequency modification methodology based on TEChnical Operational and Organizational factors. The potential of such methodology is described also in terms of support to risk based decision making for Oil&Gas integrated operations.

1. Introduction

The safety enhancement of Oil & Gas (O&G) process facilities asks for more advanced tools for hazard identification (Paltrinieri et al., 2015a) and Quantitative Risk Assessment (QRA) (Crawley and Grant, 1997). For this purpose, the use of risk indicators based on the continuous learning from events occurring during the lifecycle of the plant and inspection of safety critical elements may allow hazard and risk assessment to assume both dynamic and proactive features. In fact, appropriate set of indicators collected on a regular basis can provide information on the overall risk variation (Health and Safety Executive, 2006). Moreover, human and organizational factors often represent the underlying causes of accidents and their monitoring through indicators may enable risk assessment with proactive capabilities (Øien et al., 2010). In several major accidents, hindsight has shown that if the available early warnings had been detected and managed in advance, the unwanted events could have been avoided, such as in the case of Buncefield accident occurred in 2005, as documented by Paltrinieri et al. (2015b).
This contribution addresses approaches of dynamic risk assessment based on proactive indicators, which aim to enable recognition of early warning signals in time to reduce major accident risk. Techniques for the development of safety or risk indicators are first presented, followed by descriptions of methodologies for aggregating and relating such indicators to the overall risk level. A methodology for the evaluation and update of expected release frequencies is taken as example of last generation techniques. The methodology aiming to support dynamic risk assessment studies is named TEC2O – Frequency modification methodology based on TEChnical Operational and Organizational factors. The potential of such methodology is described also in terms of support to risk based decision making for O&G integrated operations.

2. Background on risk indicators

2.1 Classification of indicators

Appropriate sets of indicators collected and evaluated on a regular basis can provide information on the overall risk level variation. Such continuous assessment is nowadays improved by advanced IT technologies allowing for real-time data sharing, process and visualization of related information and support to decision making. However, the choice of indicators may affect the ability to control risk (proactivity), rather than just reporting its increase after an unwanted event has occurred (reactivity). The former may be addressed by a set of indicators that are mainly leading, while the latter may be addressed by a set of indicators that are mainly lagging.

Leading indicators are a form of active monitoring of key events or activities that are essential to deliver the desired safety outcome (Health and Safety Executive, 2006). They represent early deviations from the ideal situation that can lead to further escalation of negative consequences. Human and organizational factors often (but not always) represent such underlying causes. For this reason, the adoption of indicators addressing human and organizational factors may enable risk assessment with proactive capabilities. In practice, it is often experienced that indicators on technical equipment can be automatically retrieved from online systems such as e.g. maintenance management systems and condition monitoring systems. Indicators on human and organizational factors are generally more difficult to obtain and will often rely on manual input and assessment.

Lagging indicators are a form of reactive monitoring requiring reporting and investigation of specific incidents and events to discover weaknesses in the system. Lagging indicators show when a desired safety outcome has failed, or has not been achieved, providing an important feedback from the system (Health and Safety Executive, 2006). For this reason, they should be coupled with the leading indicators in order to more comprehensively assess risk. The approaches for the development of safety/risk indicators covering Technical, Human and Organizational (THO) causes may be grouped in the classes shown in Table 1.

Table 1: Classes of approaches for dynamic risk assessment through monitoring of Technical, Human and Organizational (THO) factors

Class	Perspective	Description
I	Retrospective	Indicators are developed on the basis of the effect of THO factors in past accidents, and correlation with the overall safety is assumed
II	Predictive	Indicators are defined on the basis of risk models for the potential accident scenarios addressed, and the connection to the overall risk level is logically supported
III	Aggregated	Adoption of an aggregated set of THO indicators, based on expert judgement, accident analysis and risk modelling
IV	Aggregated	Adoption of ad hoc indicators for proactive risk assessment based on expert judgement, accident analysis and risk modelling

Class I and II approaches are limited to the monitoring of indicators in a retrospective and predictive perspective, respectively. Consequently, correlation with the overall risk of the system is only assumed.

In order to accurately assess variations of the overall risk level, which may be expressed with different risk metrics (Johansen and Rausand, 2012), specific techniques aggregating the information provided by the indicators have been defined. Classes III and IV in Table 1 group the previous approaches, allowing for a more reliable evaluation of risk on a real-time basis. The main difference between classes III and IV in terms of risk evaluation is in the development and use of indicators. In class III, limited sets of risk indicators may not allow comprehensive coverage of THO factors, while the class IV approach employs ad hoc indicators for proactive risk assessment.

A methodology for the evaluation and update of expected release frequencies is hereby taken as example of last generation techniques.

2.2 Frequency modification as a dynamic risk model

Quantitative risk assessment is usually aimed at representing the initial risk status of a chemical process facility under analysis, both in terms of frequency (F) and expected consequence severity (M, namely “magnitude”). According to Crowl and Louvar (2002), the risk may be expressed as follows:

$$R = F \times M \quad (1)$$

While M is associated to a potential for damage intrinsic in the facility under consideration (considering constant release severity and plant population). Frequency F may be subject to remarkable variation due to ageing, corrosion, fatigue, poor safety culture and other dynamic factors. In fact, the frequency term F takes into account the failure of safety systems limiting the occurrence of the accidents. Hence, we may consider risk as a time-evolving parameter as follows:

$$R(t) = F(t) \times M_0 \quad (2)$$

where M_0 is a constant level of damage and F(t) represents the possible frequency variation in time (t). At the initial time of operation (t=0), when a first QRA is usually performed, we obtain the initial risk level (R_0) as follows:

$$R_0 = F(t=0) \times M_0 = F_0 \times M_0 \quad (3)$$

Combining Eq(2) and Eq(3), we obtain:

$$R(t)/R_0 \cong F(t)/F_0 \equiv \Omega(t) \quad (4)$$

Hence, the relative variation of risk level is associated with the modification of the initial frequency value F_0 through a frequency modification factor *Ω(t)* that changes during the lifetime of the plant. The initial frequency value F_0 is usually indicated as "baseline frequency" and it is derived from standard literature databases or obtained through "parts count" (Pitblado et al., 2011).
The modification factor *Ω(t)* is a parameter updated in time and aimed at considering technical, human and organizational aspects, which are related to increase or decrease of the failure likelihood. Several examples of frequency modification methods are available in the literature, such as CCPS method (CCPS, 2000); the modification factors proposed by API 581 (API, 2000); MANAGER method (Pitblado et al. 1990), and the method described by Pitblado et al. (2011) based on safety barriers scoring.
These methods can be classified as class III approaches (Table 1) due to the relatively limited focus on comprehensive and proactive indicators. However, the aggregation of multiple sets of indicators and the dynamic risk perspective introduced in Eq(4) make those methods innovative and attractive. Clearly enough, Eq(4) introduces only a simplified evaluation of the dynamic risk variation. More complex structured mathematical techniques based on Bayesian (Kalantarnia et al., 2009) and non-Bayesian (Khakzad et al., 2012) techniques are available in the literature. In the following, an example of methodology is summarized and applied to a case study in order to show its potentialities.

3. Methodology for frequency modification

3.1 Overview

The methodology is aimed at determining modification factors considering technical and managerial aspects in a dynamic perspective, thus in order to be suitable for implementation in dynamic risk assessment. The methodology is named "TEC2O", since it considers technical, operational and organizational aspects in an integrated approach in order to modify baseline accident frequency values associated to process equipment (F_0). The method is based on the following equation:

$$\Omega(t) = F(t)/F_0 = TMF(t) \times MMF(t) \quad (5)$$

in which F(t) is the timely updated accident frequency, t is the time, TMF is the Technical Modification Factor and MMF is the Management Modification Factor. TMF and MMF are obtained combining different scores, which in turn are the result of the monitoring of sound and quantitative indicators. The use of quantitative input data constitutes an advantage with respect to common literature methods based on subjective evaluations (see Section 2.2).
Indicators are converted in scores, which are based on arbitrary scale. Furthermore, in case a quantitative value of an indicator is not available, a qualitative score may be directly assigned. An important aspect is that the set of indicators proposed is changeable. It should be established in collaboration with the Company before applying the method. Finally, it is important to highlight that TEC2O must be applied to each piece of equipment of the plant under study, even though several indicators are related to the facility or the company.
The definition and evaluation of indicators is discussed elsewhere (Landucci and Paltrinieri, 2015). In the following, the main aspects related to the integration of the indicators are summarized.

3.2 Technical modification Factor (TMF)

This factor aims at synthetically account for the lifecycle of the equipment, in order to penalize "old" units, which may be more prone to result in leaks and failure due to ageing, erosion and/or corrosion phenomena. Moreover, external factors (environmental issues, seismic zone, harsh weather areas, etc.) are considered.
TMF contributes only as a worsening element, since the failure likelihood of typical mechanical and electrical components or systems increases with time, with growing rate approaching (or in some cases extending) the end of design life. Table 2 summarizes the structure of TMF, which is divided into four parts, each of them taking into account a different technical aspect, monitored through specific indicators.
Each selected technical indicator is periodically monitored. Inspections are critical in this phase in order to capture possible mechanical deterioration of the components and/or to monitor the quality of the working environment. On the basis of the indicators status, an average score is assigned to each of the four subfactors ranging from 1 to 6 (1 = good; 6 = bad). The weighted combination of the scores allows determining the overall technical score (ε), which on turn is converted into the TMF. In this work, it is suggested to use all the

technical indicators and the same weight for each of them. Clearly enough, in case an aspect is deemed not relevant by the Company, a null weight can be assigned to one or more indicators. More details are reported elsewhere (Landucci and Paltrinieri, 2016), an example of calculation is provided in Section 4.

Table 2: Summary of technical subfactors and structure of TMF

Subfactor ID	Aspect	Description
TM	Ageing	Penalization for erosion/corrosion function of process fluid, equipment design and quality of the inspection program
U	Environmental	Penalization associated to natural hazards triggering process accidents or upsets due to the poor quality of work environment
M	Construction	Penalization associated the design of the equipment item; function of equipment lifecycle and complexity
P	Process	Penalization associated to process interruptions (shut downs) and to the status of safety barriers (e.g. emergency discharge and shut down systems)

3.3 Management modification factor (MMF)

The evaluation of the management modification factor is based on the concept of resilience and follows the REWI (Resilience based Early Warning Indicators) methodology (Øien et al., 2010). Managerial aspects are related to definition of safety procedures, training and competencies of operators, safety culture, frequency of maintenance operations and communication at different levels of the organization. In order to introduce a quantitative evaluation of such factors, the REWI method proposes the use of indicators which are quantitative parameters, so they can be monitored, modified and updated in time.

Hence, according to (Øien et al., 2010), the MMF is divided into two main subfactors (see Table 3): operational (OP) and organizational (OR) subfactor. The weighted combination of the subfactor scores (also in this case ranging from 1 to 6) allows determining the overall management score (μ), which on turn is converted into the MMF. In this work, it is suggested to use the same weight for OR and OP scores. More details on the definitions of indicators are reported elsewhere (Landucci and Paltrinieri, 2016), an example of monitoring, scoring and calculation is provided in Section 4.

Table 3: Summary of management subfactors, indicators and structure of MMF.

Subfactor	Aspect	Reference indicators adopted in the case studies
OP	Operational	OP1 - Average no. of hours system training last 3 months
		OP2 - No. of tool-box meetings last month
		OP3 - Maximum no. of simultaneous operations (SIMOPS) last month
		OP4 - No. of emergency preparedness exercises last three months
OR	Organizational	OR1 - No. of procedures not up to date
		OR2 - Number of unscheduled maintenance on safety systems
		OR3 - No. of process and plant changes/modifications last month
		OR4 - Amount of overtime worked

3.4 A case study

In order to exemplify the methodology application, a sample case study was defined. The analysis focused on a crude oil desalter of an offshore platform, located in a non-seismic zone, with ambient temperature ranging from -10 to 30°C. Possible severe waves and storms may affect the area. The case study is aimed at determining the normalized accident frequency (namely, Ω, see Eq(5)) during 10 years of operations.

Beside the technical indicators and scores, the management indicators, both operational and organizational summarized in Table 3 are also monitored. For the sake of simplicity, a schedule of random events was associated to the desalter and to the facility as a whole. Those data, summarized in Figure 1, were used as input for the evaluation of indicators and the quantification of the case study.

4. Results and discussion

On the basis of the events affecting the facility under consideration and defined in Figure 1, the relevant indicators were monitored and scored according to the TEC2O procedure summarized in Section 3. The indicators dynamic behaviour is summarized in Figure 2. Due to insufficient inspection quality and deterioration of safety critical components, a worsening of technical indicators was determined. Lack of training and ineffective design of operations led also to the worsening of managerial indicators. This constitutes an example of class I and II indicators monitoring, through the assignment of the scores.

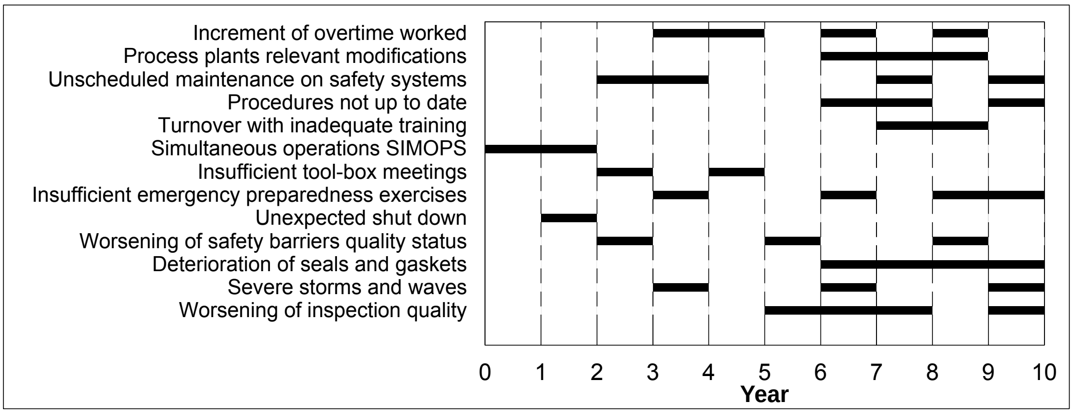

Figure 1: Schedule of events (represented by the black lines) considered for the demonstration case study.

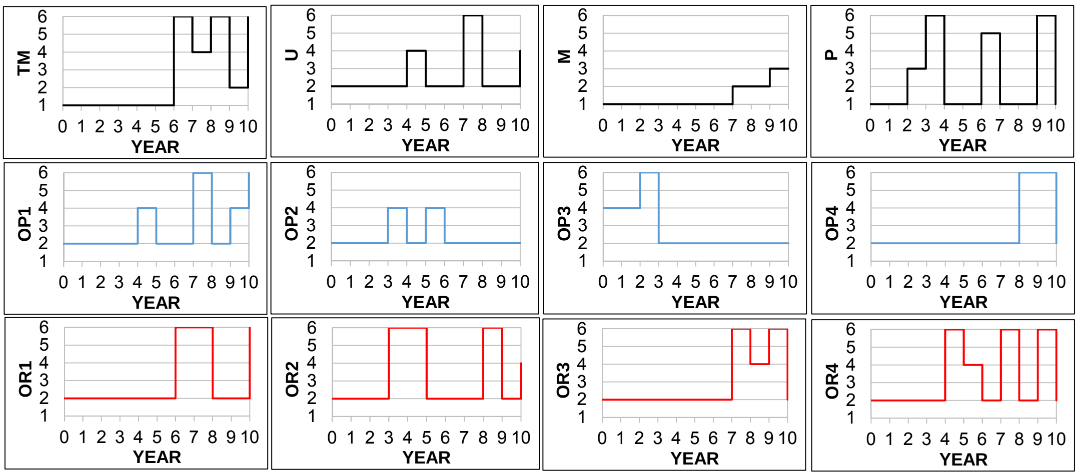

Figure 2: Summary of the indicators scores (ranging between 1 and 6; 1 = good and 6 = bad) assigned on the basis of the monitored indicators in the dynamic case study. Technical and management indicators are described in Table 2 and Table 3 respectively.

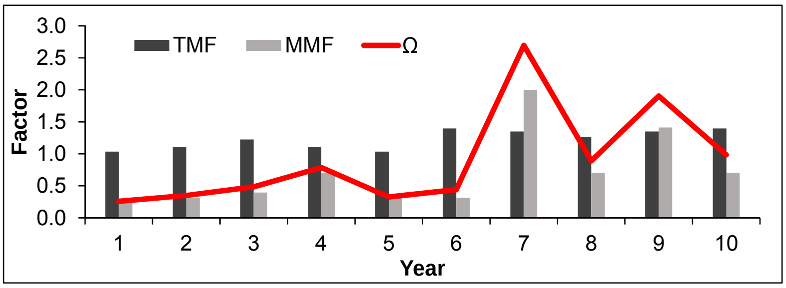

Figure 3: Results of the case study: Technical modification factor (TMF), Management modification factor (MMF), accident frequency value normalized with respect to the baseline frequency adopted in the QRA (Ω).

The scores of the indicators were then combined into the aggregated frequency modification factors, which are summarized in Figure 3. TMF can only be subjected to an increment to the baseline situation during the lifecycle of the plant (e.g., TMF>1). Relevant increases are following the worsening of inspection and work environment quality, especially at the end of the analysed 10 years. Despite the technical indicators are worsening, the management indicators lead to low value of the MMF, which never exceed the unity in the first 6 years. Nevertheless, mainly due to the worsening of organizational indicators associated to plant modification and work organization, MMF increases in the last part of the period considered.

Combining TMF and MMF according to Eq(5), the resultant modified frequency is evaluated. Figure 3 shows the normalized frequency value Ω. In the considered case, the accident likelihood is severely affected by managerial issues, which lead to a worsening of accident frequency of about 3 times with respect to the baseline value. On the same time, when MMF is kept low due to efficient management system (e.g., during the first 6 years), the accident likelihood is reduced by one order of magnitude. This is in accordance with the MANAGER method (Pitblado et al., 1990), which associates a similar modification factor for the facilities in which the safety management is more effective than in average locations.
Finally, it is worth to mention that uncertainties and limitations in the method are mainly related to data collection effectiveness, which involves the commitment of the Company, the scoring and weighting process and the translation of scores into frequency values. In the present work, single point experts' estimate were adopted, which stability was tested according to the sensitivity analysis carried out by Landucci and Paltrinieri (2015).

5. Conclusions and future works

In the present work, the adoption of safety/risk indicators as proactive tools to support dynamic risk assessment was discussed. Four classes of approaches have been described, representing different levels of connection to the overall risk picture of a facility under analysis, ranging from the techniques of safety indicator development, whose connection is assumed on the basis of past accident analysis, to dynamic aggregation methodologies based on comprehensive sets of technical, human and organizational indicators. In particular, a representative example of the latter has been presented and its capability to support safety decision-making and prevent potential human and organizational failure has been described. The analysis of the case study exemplified the application of the method, which may be used as a novel decision-making tool based on monitoring, promoting the involvement of personnel and management.

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