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Application of a fuzzy inference system for functional failure risk rank estimation: RBM of rotating equipment and instrumentation

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ABSTRACT

An increased focus on risk based maintenance (RBM) optimization has been prompted in the offshore oil and gas (O&G) production and process industry due to the currently existing regulations and guidelines on preventing the functional failure risk (FFR) of rotating equipment and instrumentation. The RBM optimization approach prioritizes functions based on the potential risk of a given functional failure. Then, the equipment and instrumentation connected to the different functions are assigned with appropriate maintenance routines according to the potential risk of corresponding functional failure. This manuscript focuses on mitigating the suboptimal prioritizations made in implementing petroleum safety authority (PSA) specified regulations and NORSOK standard Z008 specified guidelines. It is mandatory to follow these to prevent functional failures on offshore O&G production and process facilities (P&PFs) operational on the Norwegian Continental Shelf (NCS). This manuscript suggests a fuzzy inference system (FIS) to minimize the suboptimal prioritizations of functions in the FFR analysis using an illustrative tailor-made risk matrix. This risk matrix has been developed to be similar to currently existing tailor-made risk matrices that have derived from Z008 guidelines and which have been used for FFR in different P&PF owner organizations operational on the NCS. Membership functions and the rule base were developed utilizing Z008 guidelines, data, experience, intuition and intentions of maintenance engineers. A risk rank calculation has been performed using the suggested FIS. The results indicate how the proposed approach helps in simplifying and making a more reliable and uniform FFR estimation.

1. Introduction

The operation of an oil and gas (O&G) production and process facility (P&PF) involves significantly complex systems, sub-systems and equipment (Guo, Gao, Yang, & Kang, 2009). Inherently, the process media in an O&G P&PF are inflammable, explosive and toxic. Hence, a major unpredictable failure of the equipment will lead to serious economic loss, environmental pollution and catastrophic consequences to health and safety, not only to the personnel at work but also to residents in the vicinity (Kwon, 2006; Ratnayake, 2012a). In this context, performing appropriate maintenance via effective and efficient planning is vital to ensure that the equipment keeps running safely within anticipated threshold limits, preventing losses in the O&G production and process industry (Ratnayake & Markeset, 2010). In this context, risk based maintenance (RBM) provides the backbone to optimize maintenance planning. It is a global analysis approach for the optimization of maintenance activities which was initially [Note: the integration of risk within maintenance planning was firstly named Risk Focused Maintenance (RFM)] used for the maintenance of military equipment (Department of Defense, 1980; Mili, Bassettoa, Siadatb, & Tollenaerea, 2009). RBM defines maintenance action priority in relation to the level of estimated risk and improves the maintenance planning in three modules: risk estimation, risk evaluation and maintenance planning (Khan & Haddara, 2003; Tomic, 1993). The aforementioned modules involve: the identification of different failure scenarios, their potential consequence for the system, the determination of associated risk and, finally, maintenance activity prioritization by taking risk level aspects into consideration. Researchers (Arunraj & Maiti, 2007; Khan & Haddara, 2004; Khan, Sadiq, & Haddara, 2004; Krishnasamy, Khan, & Haddara, 2005) have also reported the application of RBM in improving the schedule of maintenance operations to mitigate potential failure risk. NORSOK Standard Z008 suggests an RMB approach and defines it as a procedure which aims to identify equipment that could have the greatest effect on an operation once it fails to function (Z008, 2011). The Z008 guidelines enable maintenance activity planners to determine the relative priority and

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urgency of the repairs/maintenance and decide if it is worthwhile to invest extra resources. Hence, using Z008, managers can properly formulate maintenance plans based on the functional failure risk (FFR) evaluation result of different equipment.

In RBM analysis, relatively few quantitative mathematical models for risk evaluation have been developed in the context of maintenance planning (Marhavilas, Koulouriotisb, & Gemenib, 2011). Usually, risk evaluation is treated with qualitative methodology (which may be based on quantitative data) and based on experts' knowledge, both of which result in a rather rough (or ad hoc) evaluation leading to suboptimal assessments and time consumption, variability and great demands on effort (Bertolini, Bevilacqua, Ciarapica, & Giacchetta, 2009; Braglia, Frosolini, & Montanari, 2003). The results of the risk evaluation are inherently expressed in terms of a digital form: "agreed" or "disagreed". This hinders the incorporation of the fuzziness present (such as "partly agree' or "partly disagree") due to the uncertainty and vagueness of the evaluation factors involved in risk assessments (Mure & Demichela, 2009; Sharma, Kumar, & Kumar, 2005). In this context, it is possible to consider both quantitative data and vague or imprecisely defined qualitative information in a risk assessment in a consistent manner by integrating fuzzy set theory (Sharma et al., 2005). Hence, it is vital to incorporate fuzzy set theory in RBM planning as it allows imprecise information to be treated in a consistent manner.

Basically, a fuzzy membership function (MF) plots values of a crisp range between 0 and 1, which enables the degree of vagueness or uncertainty that has been associated with conventional crisp sets to be represented (Sharma et al., 2005). Researchers such as Bragli et al. (2003), Bertolini et al. (2009), Guo et al. (2009), Kuo (1995), Li, Chen, Daib, and Lib (2010), Mure and Demichela (2009), Pinto (2014), Ratnayake (2013), Schwartz, Kaufman, and Schwartz (2004), Seneviratne and Ratnayake (2013, 2012) and Suresh and Mujumdar (2004) have proposed risk prediction approaches incorporating fuzzy set theory.

This manuscript illustrates the use of a fuzzy set theory-based consistent approach, estimating the FFR, to enhance the effectiveness of RBM planning. An illustrative case study has been performed for an engineering contractor which provides RBM planning services to P&PF owners. A risk matrix has been adopted from one of the P&PF owners which obtains RBM planning services for P&PFs. It is a tailor-made version, particular to the selected P&PF owner, which was originally developed in accordance with the guidelines available in Z008. A fuzzy inference system (FIS) has been proposed to minimize: rough (or ad hoc) evaluation leading to suboptimal assessments. It also supports (Li et al., 2010) a reduction in time consumption, variability, and the effort required to estimate FFR in RBM planning, which involves both quantitative data and vague or imprecisely defined qualitative information. A rule base has been developed using the adopted risk matrix. An FFR rank estimation approach has been presented to indicate the effectiveness of the suggested FIS and the possibility of integrating it in an existing structured information management system (SIMS).

2. RBM Planning: role of safety regulations and Z008 guidelines

2.1. Role of safety regulations

The safety regulations and guidelines pertaining to petroleum activities [i.e. oil and gas (O&G)] on the Norwegian Continental Shelf suggest that facilities' systems and equipment should be prioritized in relation to the potential health, safety and environmental (HSE) consequences due to functional failures (Ptil, 2011). The responsibility for carrying out the aforementioned prioritization based on the potential FFR on an O&G P&PF lies with the particular asset owner (i.e. the operator company), which owns the particular P&PF. Currently, the P&PF owner organizations operational on the NCS outsource maintenance activity planning based on FFR to external engineering service providers (i.e. engineering contractor companies) (Ratnayake, 2012b). At this time, the various fault modes associated with failure causes and failure mechanisms, and the probability of failure for the individual fault mode, are estimated by making use of expert knowledge and the available data sources which collect and exchange reliability data (e.g. OREDA – Offshore REliability DAta). The prioritization maintenance routines on systems, sub-systems and equipment on P&PFs are performed Based on the estimated probability of failure and consequence of failure, (Amin, Byington, & Watson, 2005). The main focus of such a prioritization is to use FFR analysis recommendations as a basis in choosing maintenance strategies (i.e. periodic, 24/7 condition monitoring, etc.) and maintenance frequencies, in ranking different maintenance activities within a selected maintenance strategy and finally, in evaluating the need for spare parts.

2.2. Role of NORSOK standard Z008 in RBM

NORSOK standard Z008 provides basic guidelines for performing risk based maintenance (RBM) planning via a comprehensive framework(s) to prioritize maintenance activities for systems, subsystems and equipment installed on the P&PFs of the Norwegian petroleum industry (Z008, 2011). In essence it covers the design phase, preparation for operations and operational phase of offshore topside, sub-sea production and O&G terminals. The standard uses risk assessment as the guiding principle for prioritizing maintenance in order to optimize the cost of inspection, maintenance and operation as well as to minimize the risk of functional failures. It has been suggested that the RBM activity (or routine) prioritizations are performed according to defined criteria. The criteria are supposed to be tailor-made in accordance with a particular P&PF owner organization's asset maintenance policy and aligned with Z008 guidelines to minimize health, safety & environment (HSE), production and cost related challenges (Ptil, 2011). The starting point of such a prioritization is to adapt a risk matrix (i.e. aligned with Z008 guidelines) along with possible ranges or linguistic terms to perform FFR assessments. As there is no means to study the boundary of each range or level of linguistic term, engineering practice reveals that final FFR assessments and corresponding prioritization of functions tend to be suboptimal. Hence, the aforementioned cause suboptimal maintenance routines leading to unnecessary maintenance (i.e. leading to higher maintenance costs and making systems worse than before due to inherited human error) or lack of maintenance leading to an increase in FFR (i.e. increase in operational and HSE related costs due to the potential failures of different functions).

3. Challenges in RBM planning

Table 1 illustrates the Z008 provided guidelines for making a tailor-made risk matrix particular to a P&PF owner organization in order to perform FFR assessments and make RBM decisions (Z008, 2011).

However, when the FFR analysis has been carried out, there is no formal mechanism to incorporate data and information at the boundaries of the risk categories (i.e. alternatively at the boundaries of the ranges and levels of linguistic data). Especially, a major difficulty lies in classifying the consequences and frequencies of a potential functional failure along the boundaries from high (H) to