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# Risk-based maintenance backlog

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ABSTRACT: A relevant issue in manufacturing and production seems to be "silo"-organisations and "silo"-planning with lack of coordination between departments. Integrated Planning (IPL) is a concept that aims to cope with this "silo"-problem. With the ground-breaking potentials from Industry 4.0 it should be expected that the advancement of IPL will speed up in development and implementation in companies. To manage IPL sound Key Performance Indicators (KPIs) must be implemented and established in the company. A promising indicator for IPL is Maintenance Backlog (MB). A strength of this indicator is the capability to be modelled with Risk OMT (Risk modelling—Integration of Organisational, human and Technical factors). It remains to investigate how MB can be modelled to a Quantitative Risk Analysis (QRA). The main objective of this article is to develop a model of MB in QRA. In particular the article demonstrates a case study of a production system where both Fault Tree Analysis (FTA), and Event Tree Analysis (ETA) is modelled. The article discusses the demonstration results and evaluate how potentials in Industry 4.0 can support QRA.

## 1 INTRODUCTION

The Oil & Gas (O&G) industry has experienced challenges with the demand of increasing oil production, lowering operating costs and life extension (Ramstad et al., 2010). These challenges have among other efforts resulted in the concept Integrated Operations (IO) and is described to be a new way of doing business (Rosendahl and Hepsø, 2013). This concept has further resulted in the Center for Integrated Operations in the petroleum industry (IO Center) where one important issue is to go from "silo organisations" towards integrated operation of all the relevant organisations (IO Center, 2012). When transferring the IO principle into the planning domain, leads us to the concept *Integrated Planning* (IPL) (Ramstad et al., 2010). In the planning domain the "silo" problem is also present.

The problem with "silo" planning in O&G industry is lack of coordination across domains and organisations (Rosendahl and Hepsø, 2013). In particular, lack of IPL results in limited resources, system failures and unscheduled maintenance (Wahl and Sleire, 2009). It is also argued that other disciplines such as drilling may affect maintenance (Sleire and Wahl, 2008). The maintenance backlog (MB) is according to Øien and Schjølberg (2009) and Meland et al. (2009) to be represented in the ageing phase for O&G facility and should be controlled at that stage. In addition, the Petroleum Safety Authority (PSA) Norway measures MB systematically for Oil companies at the Norwegian Continental Shelf (Petroleumstilsynet, 2012). In fact, according to PSA, maintenance critical backlog is regarded as a potential for major accidents.

A case study of indicators related to IPL that are applied in the O&G industry has been performed (Wahl and Sleire, 2009). Plan attainment was one type of indicator and can be related to maintenance backlog. More research for improving indicators for plan performance is concluded (Wahl and Sleire, 2009). However it is not clear in this case study how these indicators are modelled to a Quantitative Risk Analysis (QRA).

In risk modelling, the Risk OMT (Risk modelling—Integration of Organisational, human and Technical factors) model has been developed by Vinnem et al. (2012) and evaluated though a case study (Gran et al., 2012). In this model, a Bayesian belief network is applied to structure two levels of Risk Influencing Factors (RIFs) connected to the basic events in QRA. Also, the principles for updating the risk picture with a QRA-basis have been demonstrated (Vatn, 2014). The Risk OMT seems to be a promising model for a dynamic risk barometer based on indicators (Paltrinieri et al., 2017, Paltrinieri et al., 2014).

Due to different views of the term "maintenance backlog" and how it is modelled and the relevance for IPL, a novel model for MB of physical assets has been recently developed and structured in a framework for IPL (Rødseth and Schjølberg, 2017). Furthermore, the Risk OMT was tested for MB in a reliability model, demonstrating that the risk aspect is included for MB. In the Risk OMT model proposed by Rødseth and Schjølberg (2017) the RIF structure adjusted the level of MB after evaluating the RIF of *people* such as the skills to the craft technicians and the RIF of *tools* they use in maintenance planning. It remains however to investigate how MB can be evaluated as a RIF itself and connected to the QRA.

With the potentials within Industry 4.0 it would be expected that enterprises establish Cyber Physical Systems (CPS) where the physical world and the virtual world are converging (Kagermann et al., 2013, Monostori, 2014).

To implement the potentials from Industry 4.0 an architecture for CPS should be established in the organisation (Lee et al., 2015). Nevertheless, more effort is needed to investigate more in detail how Risk OMT can be adapted to such an architecture.

The main objective of this article is to develop a model of MB in QRA. To achieve this main objective following sub-objectives have been outlined:

1. Develop a general model that connects MB with QRA.
2. Test the model with a case example.
3. Propose how the model can be improved with support from the potentials in Industry 4.0.

The remainder of this article is structured as follows: Section 2 presents the CPS as a potential in Industry 4.0, Section 3 presents an example case with a corresponding risk model developed in Section 4. The results from the example case is presented in Section 5. Further, Section 6 provides a discussion of how the results can be related to CPS where concluding remarks are made in Section 7.

## 2 CPS AS A POTENTIAL IN INDUSTRY 4.0

With the trend of digitalizing manufacturing, Industry 4.0 offers several promising technologies. An essential element in Industry 4.0 is convergence of the physical world and the virtual world represented in CPS (Kagermann et al., 2013). This enables network resources, information, physical assets and people to create Internet of Things (IoT) and Internet of Services.

Maintenance clearly positions in Industry 4.0 where both predictive and remote maintenance provides value creation in enterprises in terms of improved asset utilization and reduced maintenance costs (McKinsey & Company, 2015). For maintenance, the 5C architecture seems to be promising as a CPS architecture (Lee et al., 2015, Lee et al., 2017). This architecture has also been tested for manufacturing (Lee et al., 2017) and process industry (Rødseth et al., 2016). The 5C architecture forms a pyramid with following levels:

- Level 1: *Connection*. Data collection from e.g. sensors connected to machines.
- Level 2: *Conversion*. Data converted into useful information, e.g. calculations of vibration data.
- Level 3: *Cyber*. The information is connected to internet where advanced analytics can take place in terms of e.g. fleet analytics.
- Level 4: *Cognition*. To support a decision, visual interfaces such as dashboards and key performance indicators are necessary.
- Level 5: *Configuration*. Decision-making is supported through e.g. "digital advices" for conducting maintenance activities.

This architecture has also been proposed to be a sound structure for the maintenance model Deep Digital Maintenance (DDM) (Rødseth et al., 2017). DDM comprises the module planning where it remains to elaborate how MB can improve the planning function for DDM.

## 3 DESCRIPTION OF SYSTEM AND AN EXAMPLE CASE

In this article a heat exchanger with a barrier system is outlined in Figure 1 as an example. The system is a heat exchanger with a barrier system. The heat exchanger receives gas from two processes, process 1 and 2. If there is a leakage from the heat exchanger both valve 1 and valve 2 must close in order to avoid further leakages. Figure 2 further

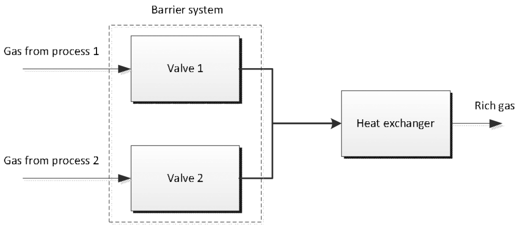

Figure 1. Illustration of a heat exchanger with a barrier system.

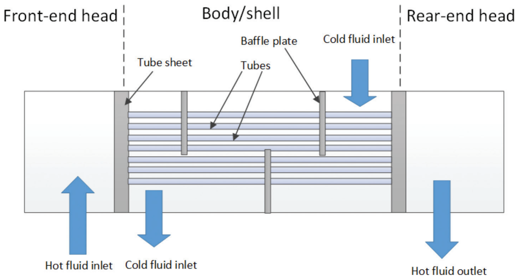

Figure 2. Illustration of a heat exchanger, adapted from (Utne et al., 2012).

describes the heat exchanger system in details (Utne et al., 2012).

This heat exchanger is a single-pass tube, baffled single-pass shell, shell-and-tube heat exchanger designed to provide counter flow conditions. In addition, this type of heat exchanger is one of the most commonly used in offshore oil and gas processing plants. In the case study we will consider an example case of the tubes in the heat exchanger where the model developed is tested with example data. The tubes constitute a bundle, meaning that no single tube can be solely replaced. If there is leakage from a tube it will be plugged. However, this will decrease the efficiency of the heat exchanger and at some point the whole bundle will be changed. This will then set the efficiency back to 100% of the design efficiency.

For the heat exchanger it is assumed that leakage only occurs from tubes and is located in the shell section. For the barrier system, only valve 1 is of interest. For the heat exchanger and the valves there exists a specific maintenance programme coordinated by the maintenance management.

## 4 RISK MODELLING

The core of the RISK OMT is modelling RIFs and how these affect the operational barriers. In this paper the RIFs are identified in the tasks in the maintenance programme and affect both the barriers (valves) and the production facility (heat exchanger). A RIF is defined by (Øien, 2001) to be *"an aspect (event/condition) of a system or an activity that affects the risk level of this system/activity"*. Further a RIF is a theoretical variable that can be measured.

The risk picture is illustrated in Figure 3. The initiating event in the QRA is leakage from shell and tube heat exchanger. This leakage is due to either leakage from front-end head section, rear-end head section or shell section.

In this article the shell section denoted as basic event 3 is further studied. It is assumed that the frequency of leakage from front-end head section and rear-end head section is negligible. When the initiating event occurs the barrier system shall shut down the gas supply. Both valve 1 and valve 2 must function in order to avoid a safety critical event.

The worst scenario in the QRA occurs with an impact of both a safety critical and economic critical consequence shown with the dotted circle in Figure 3. For this scenario the annual expected frequency is of interest.

Figure 4 presents the FTA for the initiating event with leakage from the shell and tube heat exchanger, while Figure 5 presents the barrier system structured with FTA. The barrier system comprises two shutdown valves where both must fail.

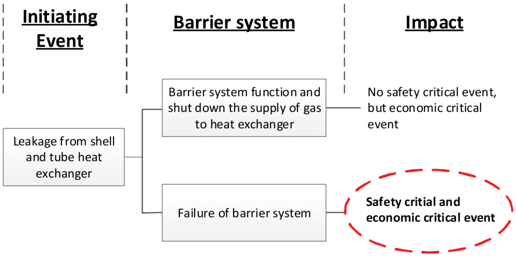

Figure 3. The total risk picture in QRA.

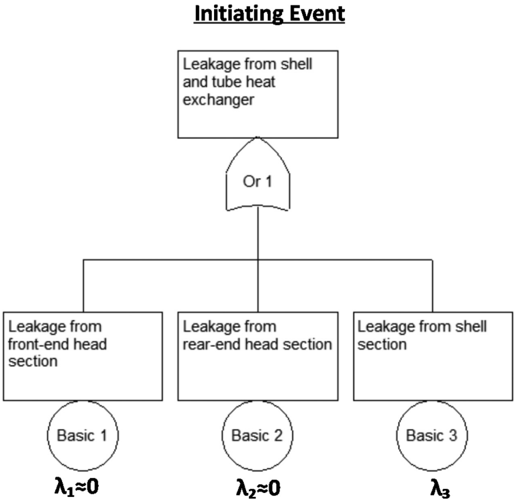

Figure 4. FTA of initialing event.

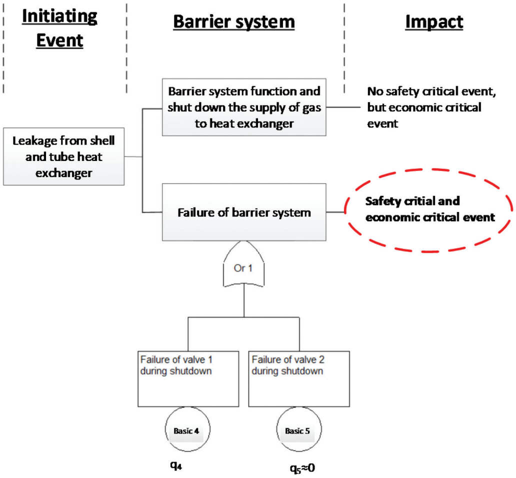

Figure 5. FTA of barrier system.

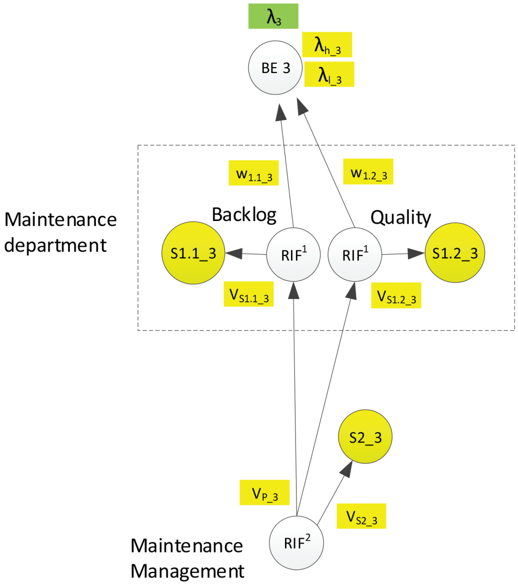

Figure 6. RIF structure that connects to QRA.

Figure 6 presents the RIF structure which is connected to the basic event 3 in the FTA from Figure 4. The same design of the RIF structure is also connected to the basic event 4 in the FTA from Figure 5. For each RIF, a score, S from A-F is observed and a variance, Vs of the score is evaluated.

The variance of the score reflects on how accurate the observation is to the “real” RIF. The RIF structure consists of two levels where there is a structural dependency Vp between level 2 parent RIF and level 1 child RIFs. At level 1 the RIFs are weighted with weight w based on expert judgment. The RIF structure is further described in this section with elaboration of Risk OMT.

## 4.1 *Level 2 RIF*

Maintenance management is defined as (CEN, 2010) “*all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics*”. This level is on the organisational level and affects the operative level 1.

## 4.2 *Level 1 RIFs*

### 4.2.1 *Maintenance backlog*

Maintenance backlog is defined as (Rødseth and Schjølberg, 2017) “*the amount of unfulfilled demands at a given point of time in explicit reference to predefined standards to be achieved. The demands comprise both demands for the technical condition itself and demand in meeting the planned due dates in the work orders. Furthermore, maintenance backlog can be expressed in functional (non-monetary) or monetary terms and it refers to single components, sub-assets or to the whole asset*”.

Table 1. Score and evaluation criteria.

| Score | Evaluation criteria |
|---|---|
| A | «Best case» score |
| B | |
| C | «Normal case» score |
| D | |
| E | |
| F | «Worst case» score |

It is proposed by Rødseth and Schjølberg (2017) that maintenance backlog can have a financial perspective that is both based on work orders and the technical condition of the facility based on the understanding of maintenance backlog from petroleum authorities (Petroleumstilsynet, 2016) and road authorities (Weninger-Vycudil et al., 2009) respectively. When providing a score of maintenance backlog, both the deviation of expected wok completed from the work orders and the technical condition should be evaluated.

Table 1 presents the score and evaluation criteria for maintenance backlog.

### 4.2.2 *Maintenance quality*

Maintenance quality is an aggregation of all factors that affects the quality of the service provided in the maintenance task. A comprehensive list of factors that can be related to maintenance quality has been outlined (Rødseth and Schjølberg, 2017). The list of relevant factors for maintenance quality can also be based on the findings from audits (Øien et al., 2010):

1. Classification
2. Documentation
3. Use of classification
4. Competence
5. Maintenance efficiency evaluation

The evaluation of the score, variance and weight of this RIF is based on questionnaires and interviews for the assessing the “soft” issues like competence and maintenance efficiency evaluation. For the more “hard” issues like classification the observation of the score is based on direct observations in the organisation.

### 4.3 *Standard calculation of two level 1 RIFs and one level 2 RIF*

When calculating the basic event with the RIF structure presented in Figure 6 a mathematical approach is needed. This approach has also been presented by (Rødseth and Schjølberg, 2017). It is here included for completeness. Further details and foundations for this approach and the formulas are elaborated by (Vatn, 2013). The approach comprises 6 stages for calculating basic event $q_i$ and can be summarized as follows:

1. Perform an expert judgement and evaluate the score of each RIF in the range of A-F, the variances, the weights $w_i$ and values for q.
2. Map the scores into values in the interval [0,1] with following scores:
   A = [1/12], B = [3/12], C = [5/12], D = [7/12], E = [9/12], F = [11/12]. The range in the vector is then: [1/12, 3/12, 5/12, 7/12, 9/12, 11/12].
3. Calculate the posterior distribution of parents RIF based on following formulas where Jeffreys prior is used with the prior parameters $\alpha_0 = \beta_0 = 0.5$:

$$\alpha = \alpha_0 + s^2(1-s) \big/ V_s \tag{1}$$

$$\beta = \beta_0 + s(1-s)^2 \big/ V_s \tag{2}$$

4. Calculate the prior distributions $\alpha_0$ and $\beta_0$ of child RIFs based on following equations:

$$\beta_0 = \left( \frac{p(1-p)}{V_p} - 1 \right)(1-p) \tag{3}$$

$$\alpha_0 = \frac{p\beta_0}{(1-p)} \tag{4}$$

5. Calculate the weighted sum for level 1 RIFs and the expected probability for each possible combination, *i*. All the combinations are distributed in a list.
6. Apply the law of total probability and calculate the basic event with following formula of qi:

$$q = \sum_p \left[ \sum_r q_L * \left( \frac{q_H}{q_L} \right)^{\sum_j w_j * r_j} * p_{\boldsymbol{R}}(\boldsymbol{r} \mid \boldsymbol{P} = \boldsymbol{p}) \right] * p(\mathrm{p}) \tag{5}$$

### 4.4 *Modelling the basic events*

For the example case we assume that we have two independent RIF structures that affects the initial event and the barrier system in the QRA. In this case example we have two outsourced maintenance organisations that are specialised in maintenance for heat exchangers and valves. Further it is assumed that these organisations are independent from each other.

When $\lambda_3$ for basic event 3 is calculated, the frequency can also be calculated. Since the heat exchanger is regarded as a repairable unit following formula is used:

$$q_i \approx \lambda_i * MTTR_i \tag{6}$$

From basic event 3, the frequency of initiating event, IE, is of interest. Since we have one OR gate and neglect basic event 1 and 2, the frequency of the initial event can be calculated as follows:

$$\lambda_{IE} \approx \frac{q_1}{MTTR_1} + \frac{q_2}{MTTR_2} + \frac{q_3}{MTTR_3} \approx \frac{q_3}{MTTR_3} \tag{7}$$

## 5 RESULT

### 5.1 *Input data*

The input data is shown in Table 2 and Table 3, partly based on data from the OREDA handbook (Sintef and Oreda, 2009). The failure rates for the heat exchanger are collected from OREDA data base. The high and low values for $\lambda_3$ and $q_4$ is in accordance with the Risk OMT model.

### 5.2 *Result data*

The result from the example case is structured in Table 4. For the scenario, the frequency is calculated.

Table 2. Input date for basic event 3.

| Parameter | Value |
|---|---|
| $S_{1.1\_3}$ | D = 0.58333 |
| $S_{1.2\_3}$ | B = 0.25000 |
| $S_{2\_3}$ | C = 0.41667 |
| $w_{1.1\_3}$ | 0.3 |
| $w_{1.2\_3}$ | 0.7 |
| $VS_{1.1\_3}$ | 0.01 |
| $VS_{1.2\_3}$ | 0.04 |
| $VS_{2\_3}$ | 0.04 |
| $VP_3$ | 0.0025 |
| $MTTR_{\_3}$ (hours) | 3.0 |
| $\lambda_{l\_3}$ (/hours) from (Sintef and Oreda, 2009) | $0.39*10^{-6}$ |
| $\lambda_{h\_3}$ (/hours) from (Sintef and Oreda, 2009) | $23.87*10^{-6}$ |

Table 3. Input data for basic event 4.

| Parameter | Value |
|---|---|
| $S_{1.1\_4}$ | C = 0.41667 |
| $S_{1.2\_4}$ | C = 0.41667 |
| $S_{2\_4}$ | C = 0.41667 |
| $w_{1.1\_4}$ | 0.3 |
| $w_{1.2\_4}$ | 0.7 |
| $VS_{1.1\_4}$ | 0.01 |
| $VS_{1.2\_4}$ | 0.04 |
| $VS_{2\_4}$ | 0.04 |
| $VP_{\_4}$ | 0.0025 |
| $q_{h\_4}$ (/hours) | $10^{-3}$ |
| $q_{l\_4}$ (/hours) | $10^{-4}$ |

Table 4. Changes in QRA.

| Initiating event, (/hours) | Barrier system, (/hours) | Frequency in QRA (/year) |
|---|---|---|
| $\lambda_3 = \lambda_{IE} = 2.9500*10^{-6}$ | q4 = 0.0030 | $F_2 = \lambda_{IE}*q4 = \mathbf{7.75*10^{-5}}$ |

## 6 ADAPTING RISK OMT WITH CPS

The objective of this article was to develop a model of MB in QRA. With a model from Risk OMT, a structure of RIF with two levels was developed and connected to a case example of a heat exchanger. Improved maintenance quality can to some extent compensate for poor maintenance backlog. Still the organisation should strive to reduce MB in order to improve the overall risk picture of QRA of the plant.

To improve the implementation and application of the model of MB, an essential evaluation would be to what degree could this model be automated. The motivation of this automation is due to the huge amount of technical objects in a plant that is maintenance significant. Obviously some evaluations such as maintenance quality should remain manually performed by experts, but the evaluation of MB should have potential in being conducted more automatically.

Figure 7 proposes how an CPS architecture could be constructed, inspired by the 5C model from (Lee et al., 2015). At level 1 relevant data for maintenance backlog is captured in real-time from both the computerized maintenance management system and condition monitoring systems. At Level 2 the values for MB is calculated both from CMMS and condition monitoring in monetary terms in accordance to (Rødseth and Schjølberg, 2017). At level 3 the score, S is automatically evaluated based on comparing with earlier measurements of MB. In level 4 the QRA will be visualized as a risk picture. Finally in level 5 a digital advice is provided to propose reduction of maintenance backlog if necessary.

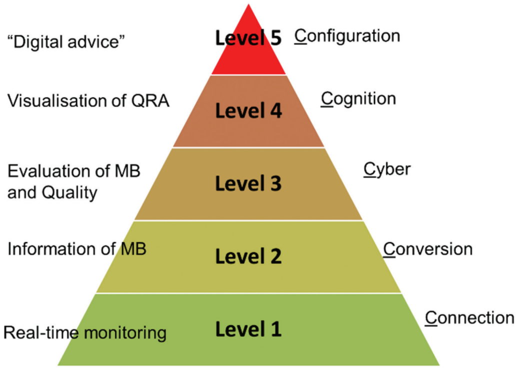

Figure 7. CPS architecture proposed for Risk OMT, inspired by the 5C model from (Lee et al., 2015).

## 7 CONCLUDING REMARKS

It is concluded in this article that the proposed model of MB in QRA should be further developed, in particular with respect to decision criteria for providing the score. In addition, a CPS architecture for industry should be established with respect to Risk OMT modelling and include it in the maintenance model DDM. Further studies of this model should also be performed not only in the O&G industry, but also in industry branches such as the maritime industry, manufacturing, process industry and the railway industry.

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