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Comparison of Risk-Based Maintenance Approaches Applied to a Natural Gas Regulating and Metering Station

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In the last decades, many researchers have directed their efforts towards the safety improvement of plants where hazardous substances are processed or handled. This attitude has led to developing strategic plans for minimizing risk and costs arising from the operations. Accidents related to hazardous substances can indeed pose a threat to human beings and the surrounding environment, therefore a reliable tool for engineering maintenance is required. This paper presents a comparison of two different Risk-Based Maintenance (RBM) approaches for prioritizing maintenance actions. The first approach consists of a classic Quantitative Risk Analysis (QRA), where standard probabilities from literature are exploited for the modeling of the different scenarios. In this study, the catastrophic rupture and three sizes of leakage have been chosen as reference scenarios for each component. The analysis is carried out through a software named Safeti (by Den Norske Veritas – German Lloyds DNV-GL), which performs calculations based on standard source, dispersion and consequence models. Safeti provides a ranking of the components based on their criticalities. In the second technique, Hierarchical Bayesian Network (HBN) is adopted to estimate the probability of failure components, while the severity is assessed via Failure, Mode, Effects and Criticality Analysis (FMECA). Subsequently costs related to each component are evaluated and a Cost Risk Priority Number (CRPN) is obtained. This comprehensive review can help maintenance engineers to reduce risks resulting from operations and pinpoint the most critical components, by using the approach that is more suitable for their case. To demonstrate the two different approaches and compare their results a Natural Gas Regulating and Metering Station (NGRMS) is considered as case of study. The results show that applying the two methods to the same plant gives different component rankings, due to their different sensitivities and settings.

1. Introduction

Natural gas is deemed as a hazardous substance due to its flammability, indeed leakages or catastrophic ruptures of devices processing natural gas can lead to dangerous events such as jet fires, pool fires, fireballs or Vapor Cloud Explosions (VCE). Besides, due to the complexity of a natural gas distribution system and its vicinity to urban areas, accidents related to the network can generate fatalities and domino effects (Han and Weng, 2011). Despite the development of renewable energy sources, the consumption of methane gas is still increasing in industrialized countries (Vianello and Maschio, 2014) and the more the network expands, the more the society relies on the safety of its operations (P. K. Dey, 2002). Hence comprehensive tools able to mitigate the risk arising from natural gas distribution system breakdowns are required to guarantee the safety of human beings and environment.

Planning maintenance and inspection activities are among the most common techniques to avoid failures and maximize the equipment availability while minimizing the total cost of the operations (Khan and Haddara, 2003). An appropriate definition of maintenance is expressed by Dhillon (2002) who identifies maintenance as all the activities required to restore the function of an item a part or a component to a given condition. In literature, several maintenance strategies are presented (Moubray, 2001), indeed during the past years maintenance has been experiencing a drastic change from only time-based methodologies to condition and risk-based approaches (Arunraj and Maiti, 2007).

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Risk-Based Maintenance (RBM) integrates the consequences of failures into the maintenance plan, prioritizing the maintenance actions based on the level of risk of each component (Ambühl and Sørensen, 2017). For its characteristics, RBM has lured the attention of several researchers during the last decades. To conduct RBM many tools have been adopted such as Fault-Tree (Krishnasamy et al., 2005), Failure Mode and Effect Analysis (Wang et al., 2012), Fuzzy-logic (Jamshidi et al., 2013) or Bayesian Network (Leoni et al., 2019). Bertolini et al. (2009) proposed another RBM approach where expert judgments and appropriate tables for severity and occurrence are exploited to identify the most critical items, events and work orders for an oil refinery. A significant amount of effort was directed towards developing RBM methodologies for oil and gas pipelines. Dynamic Bayesian Network (DBN) and Influence Diagram (ID) were adopted by Arzaghi et al. (2017) to model the probabilistic deterioration process due to fatigue crack of a subsea pipeline and then schedule the maintenance activities. Other works presented by P. Dey (2001) and Al-Khalil et al. (2005) adopt an Analytical Hierarchy Process (AHP) to evaluate the probability of failure of a cross-country pipeline and subsequently estimate the costs arising from the failure. Through these approaches, the ranking of the most critical failure causes is obtained.

Although studies have been conducted to improve the safety of Oil & Gas operations, there is still space for introducing methodologies able to prioritize maintenance actions based on the level of risk. Besides, Natural Gas Regulating and Metering Station (NGRMS), which is a pivotal part of the gas network, is still less considered than the pipeline system. To this end, the main objective of this paper is to compare two different RBM approaches capable of ranking the components based on their criticality. In the first approach, a QRA is implemented via Safeti adopting standard frequencies. For the second technique, the probability analysis is conducted via Hierarchical Bayesian Network (HBM), while a Failure Modes and Effects Criticality Analysis (FMECA) is adopted to assess the severity of each component. Introducing the failure costs the Cost Risk Priority Number (CRPN) is calculated. The advance of such models was verified on an actual example of the stochastic process of a Natural Gas Regulating and Metering Stations (NGRMS) near Florence, Italy.

In Section 2, the methodology utilized in this work has been described, while in Section 3 the results are presented. At last in Section 4 the conclusions are discussed.

2. Methodology

During this study, two different RBM approaches for prioritizing maintenance actions have been developed (Figure 1).

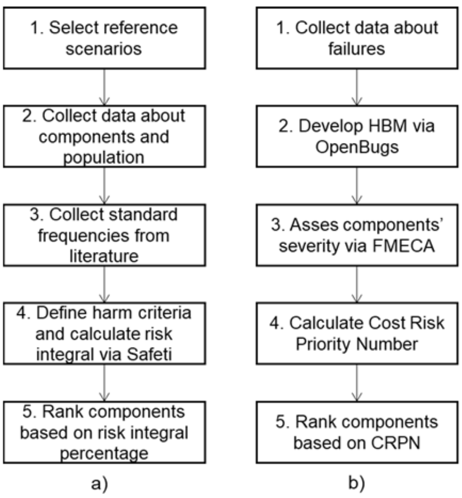

Figure 1: Flow charts of the QRA methodology (a) and the HBM methodology (b)

2.1 Quantitative Risk Analysis through Safeti

Standard source, dispersion and consequence models are exploited by Safeti to conduct the QRA. The system is defined and it is broken down into its most relevant components. The geographical location of the plant handling a hazardous substance and the plant layout are studied. For each component, four different reference scenarios have been selected (the catastrophic rupture and three sizes of leakage), while their occurrence frequencies are found in the literature. During this phase, the operating condition of each component is also assessed to develop the Event Trees (ET). Simultaneously weather parameters such as Pasquill stability, temperature and data about wind are determined, as long as population density around the plant. At last, harm criteria, which are required to estimate the risk of each scenario, are chosen and the analysis via Safeti is conducted. Based on the risk integral percentage percentage (i.e. the percentage of the total risk associated to a certain component) arising from the calculation the components are ranked.

2.2 Hierarchical Bayesian Modelling and Cost Risk Priority Number

During the first phase of this approach, the system involved in the RBM is determined, and its peculiar components and their relationships are also identified. Subsequently, data about the number of failures that occurred during a certain timespan are collected. Exploiting these data HBM is implemented via a script in OpenBugs software. HBM is defined by El-Gheriani et al. (2017) as an advanced probabilistic tool able to conduct inference based on real-world observation. HBM performs inference by applying the Bayes' theorem, given by Eq(1).

$$\pi_1(\theta|x) = \frac{f(x|\theta)\pi_0(\theta)}{\int_\theta f(x|\theta)\pi_0(\theta)d\theta} \qquad (1)$$

where θ represents the unknown parameter of interest, while $f(x|\theta)$ is called the likelihood function. $\pi_0(\theta)$ is addressed as the prior distribution of θ and $\pi_1(\theta)$ denoted the posterior distribution of θ. As stated by Kelly and Smith (2009) the prior distribution for the parameter of interest can be expressed by the Eq(2) :

$$\pi_0(\theta) = \int_\emptyset \pi_1(\theta|\varphi)\pi_2(\varphi)d\varphi \qquad (2)$$

$\pi_1(\theta|\varphi)$ is the first-stage prior of the population variability in θ, for a given value of φ. The hyper-prior distribution is denoted by $\pi_2(\varphi)$ and it considers the uncertainty of φ, which, in most cases, is a vector and its components are called hyper-parameters.
Through HBM the distributions of the probability of failure are estimated for the component of Table 3, then the mean values are evaluated for each distribution. The mean probabilities of failure are then used to assign a level of occurrence to each component based on Table 1. The severity analysis is conducted using FMECA, which is carried out to determine the consequences arising from a failure. Based on the possible outcomes of a failure, components are classified into ten categories of severity (Table 2).

Table 1: Likelihood criteria ranking

Occurrence (O)	Occurrence probability
1	<1 in 30,000
2	1 in 25,000
3	1 in 20,000
4	1 in 10,000
5	1 in 5,000
6	1 in 3,000
7	1 in 2,000
8	1 in 1,000
9	1 in 500
10	1 in 20

Table 2: Severity criteria ranking

Severity (S)	Severity of effect
1	No effect
2	Very minor effect on production
3	Minor effect on production
4	Small effect on production, repair not required
5	Moderate effect on production, repair required
6	Component performance is degraded
7	Component is severely affected, NGRMS may not operate
8	Component is inoperable with loss of primary function
9	Failure involves hazardous outcomes
10	Failure is hazardous and occurs without warning, NGRMS operation is suspended

At last, exploiting expert judgments and useful data, the cost of replacing a piece of certain equipment is evaluated and then the CRPN is calculated for each component as showed in Eq. (3):

$$CRPN = C * O * S \qquad (3)$$

Where *C* represents the cost of the component replacement, while *O* and *S* are respectively integers of occurrence and severity obtained by Table 1 and Table 2.

3. Results and discussion

To demonstrate the application of the approaches a NGRMS, operating near Florence, Italy, is adopted as a case of study. NGRMS has two main tasks: i) reducing the pressure of the gas to adapt it to the subsequent devices and ii) measuring the gas flow parameters. Inside an NGRMS there are four major groups and twelve major components, listed in Table 3.

3.1 Application of QRA to NGRMS via Safeti

Safeti is a software that allows to perform QRA for the plant where hazardous substances are handled or processed. This software is characterized by a vast field of application such as simulating gas explosion (Huang et al., 2017) or studying supercritical fluid extraction (Iovinea et al., 2020). The reference scenarios considered for the pressure regulator are illustrated in Table 4, with their relative frequencies that are based on expert judgments and several sources (Cox et al., 1990; Spouge, 2005).

Table 3: NGRMS' groups and components

Group	Component
Reduction	Pressure regulator (PR)
	Pilot
	Filter
Measuring	Pressure and Temperature Gauge (PTG)
	Calculator
	Meter
	Remote Control System (RCS)
Odorization	Tetrahydrothiophene (THT) tank
	THT pipeline
Preheating	Boiler
	Pump
	Water pipe

Table 4: Adopted scenarios and their frequencies for PR

Component	Scenario category	Frequency [Event/year]
Pressure regulator	10mm leakage	0.00012
	25mm leakage	1.10E-05
	50mm leakage	1.10E-05
	Catastrophic rupture	3.20E-06

At last, the harm criteria are chosen. Four different thermal radiation for jet fire, fireball and pool fire were considered: 1.6, 4, 12.5, 37.5 $kW/_{m^2}$. Regarding the flash fire, the population inside the Lower Flammability Level (LFL) will die with 100% probability due to direct contact with the flames, while people situated in ½ LFL will suffer only inhalation effect. Four levels of overpressure were chosen to evaluate the impact of the Vapor Cloud Explosion (VCE). The adopted evaluation criteria are reported in Table 5:

Table 5: Adopted harm criteria for the implementation of the QRA

Incident outcome	Criteria	Damage	Fatality
Flash Fire	LFL	Imminent Death	100%
	1/2LFL	Inhalation Effect	0
Pool fire, fireball, jet fire	1,6 (kW/m2)	Safe distance	0
	4 (kW/m2)	Second degree burn	1%
	12,5 (kW/m2)	Melting of plastic tubing	10%
	366 (kW/m2)	Damage to process equipment, death	100%
VCE	0,0103 bar	Glass shatter	0%
	0,02068 bar	Safe distance	0%
	0,1379 bar	Partial collapse of roof and houses	5%
	0,2068 bar	Serious injury, Fatality	100%

Safeti assesses the risk integral percentage of each scenario, then to estimate the risk integral percentage of a certain component, the risk integral of every related scenario is summed. The obtained ranking is showed in Table 6:

Table 6: Ranking obtained via QRA

Ranking	Component	Risk integral percentage
1	Filter	77.57
2	Pressure Regulator	11.48
3	THT tank	9.494
4	THT pipelines	1.451
5	Water pipe	0
6	Pump	0
7	Boiler	0

With a striking difference in the risk integral percentage, the filter is evaluated as the most critical component. On the opposite side, the pre-heating group components are the less critical, indeed they have a null risk integral, indeed leakage or catastrophic rupture provokes at most slightly burn. Between the filter and the water components, there are Pressure Regulator, THT tank and THT pipe. Accordingly, the most critical group is the methane group, indeed its components are respectively the most critical ones, thus its maintenance has the priority. The odorization group is the second most critical unit, with THT tank as the component characterized by the highest risk integral percentage.

3.2 Application of CRPN method to NGRMS

Table 8 lists the number of failures and population numbers, which are the starting data of the last approach. These values are obtained by 59 NGRMS and they are referred to a period of 6 years. Through these data, the Bayesian analysis is implemented in OpenBugs. The Bayesian inference predicts the posterior probability of failure distributions, which mean values are represented in Table 7:

Table 7: Number of failures, population number and posterior mean probability of failure of NGRMS' main components

Component	Number of failures	Population number	Posterior mean probability of failure
Pressure Regulator	17	543,120	0.00003462
Pilot	6	1,086,240	0.00001291
Filter	12	271,560	0.00005363
RCS	19	129,210	0.0001519
Meter	7	236,520	0.00004226
PTG	65	129,210	0.0005089
Calculator	47	129,210	0.0001609
THT tank	7	129,210	0.00006795
THT pipelines	3	129,210	0.0000357
Pump	38	236,520	0.0001694
Boiler	23	236,520	0.0001067
Water pipe	25	129,210	0.0002072

Values listed in Table 7 are exploited to assign to each component a level of occurrence based on Table 1. Simultaneously an FMECA is performed to evaluate the severity class of each component following Table 2. After introducing the costs obtained by the company, the CRPN is finally calculated as illustrated by Eq (3). The outcome of this technique is reported in Table 8.

Table 8: Ranking obtained via CRPN method

Ranking	Component	CRPN	Occurrence	Severity	Cost
1	THT tank	108	4	9	3
2	Boiler	75	5	5	3
3	Pressure Regulator	72	2	9	4
4	Filter	72	4	9	2
5	RCS	60	5	6	2
6	THT pipelines	54	2	9	3
7	Water pipe	32	8	2	2
8	Meter	18	3	3	2
9	Pilot	16	1	8	2
10	Calculator	15	5	3	1
11	Pump	15	5	3	1
12	PTG	12	6	2	1

The calculation depicted that the most critical component is the THT tank with a CRPN equal to 108, thus its maintenance has to be prioritized. On the other side, the less critical component is the PTG which is characterized by a CRPN of 12, which comes mostly from the occurrence level (6).

4. Conclusions

This work presents a comparative study of two different RBM approaches. These approaches can pinpoint the most critical components that maintenance must prioritize. NGRMS was chosen as a case of study to illustrate the frameworks and to underline their advantages and limitations. Software developed by DNV-GL is adopted for the first approach, where a QRA is performed. Standard frequencies of the hazardous scenarios are inserted into the software along with other required data and information. The consequence analysis is then conducted and the components are ranked based on their respective risk integral percentage. At last, the occurrence analysis conducted via HBM and the severity analysis performed by FMECA are the main parts of the second methodology. In the last part, through a combination of cost, occurrence and severity the CRPN is calculated for each component. Due to their different sensitivities, the two approaches provide different rankings. For the QRA the filter is addressed as the most critical component, while the components that belong to the pre-heating group emerged to be the less critical ones. A striking difference arises if the first ranking is compared to the second one, indeed the CRPN method gives priority to the THT tank, followed by the boiler which is one of the less critical equipment for the QRA. Further work can be carried out integrating these approaches within the ARAMIS methodology which was born as an answer for the SEVESO II directive.

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