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Risk-Based Inspection and its Application to the Optimization of Chemical Plants

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The correct design of a chemical plant does not necessarily imply a fully safe facility. Without the adequate inspections and maintenance plans, certain equipment sooner or later will collapse as a result of wear, fatigue, corrosion or other circumstances. Thus, an effective inspection plan is one of the tools considered in the operation safety programs to reduce the risk of accidents. Effective inspections can reduce risk through the decrease of the failure frequency by establishing corrective and preventive measures, which are taken into account once the inspection has identified potential failures. Generally speaking, as the investment in safety increases, the risk associated to a given plant or activity decreases and the cost of the potential accidents that can occur will probably also decrease. A methodology is proposed to optimize the inspection plans of a facility through the introduction of risk analysis as a variable. An objective function is thus established to analyse the variations in the overall costs, including the cost of the procedure and the cost of the potential accidents. This leads to an optimum situation in which the overall cost (inspection plus accident consequences) reaches a minimum. As an example, the methodology is applied to one case concerning the transportation of a toxic material. The cost of accidents has been shown to decrease significantly when at least one inspection is applied in the lifetime of the equipment, this influence being of course more important when the effectiveness of the inspection is higher.

1. Maintenance and Risk

Equipment installed at a chemical plant will suffer a decline over their lifetime due to the working conditions to which they are subjected; these can lead to corrosion, wear of rotating mechanical parts, material fatigue, damage and deformation, as well as to other problems depending on each process. In order to avoid or to minimize the probability of any failure which can affect the safety of the plant, the adequate maintenance of equipment or instruments is required. In some cases, the cost of maintenance at a chemical plant can be high, particularly when the execution of some procedures implies a certain risk. When designing a new plant, one of the main objectives is usually to minimize the capital to invest. The improvement of equipment reliability increases the initial cost of the plant, but can decrease the maintenance cost. The cost of anticipated maintenance usually appears as a fraction of the estimated construction cost for new projects 3 – 6 % of the cost of the plant and 2 to 3 % of civil works (King, 1990).

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2. Inspection Based on Risk Analysis

Inspection is actually one of the procedures applied in accident prevention as a part of safety programs. The proper use of a planned inspection program will reduce the incidents and the potential damages. The methodology of inspection based on risk analysis (IBR) provides a basis for risk management. IBR consists on taking decisions based on the frequency of inspections, level of detail and type of assessment (API, 2005). Many chemical plants have a large number of equipment, although the risk might be focused in a small percentage of such equipment. These high-risk components require significant attention, perhaps by an appropriate inspection plan. The inspection cost can be reduced by decreasing the level of effectiveness in areas that have been identified as low risk, which do not require a rigorous inspection.

A lack of inspection in chemical plants would lead to a higher risk of accidents. A significant aspect to note is that an initial investment in inspection activities implies a substantial reduction of risk, whereas there is a point from which additional investment produces a much smaller risk reduction. Not all inspection programs are equally effective in detecting the damages of equipment or services to reduce risk. However, IBR provides a methodology to determine the optimal combination of plans and frequencies. Each available plan and its effectiveness in reducing the frequency of accidents can be analyzed. Inspections can reduce risk through the reduction of the frequency of failure by the use of corrective and preventive measures, which are taken into account after the inspection has identified any possible failures.

3. Inspection and Risk

Maintenance costs can be reduced in the design stage, for example through the use of materials and equipment more resistant to corrosion. In this way, an appropriate economic balance between the probable costs of plant shutdowns and the investment cost should be performed. The risk associated to a given accident depends on two variables:

$$Risk = frequency \times magnitude\ of\ the\ consequences \quad (1)$$

Therefore, any action to reduce the risk should focus on reducing one or both variables. However, the magnitude of consequences in the event of an accident, unlike frequency, is not affected directly by the procedures.

3.1 Frequency estimates

The adjusted frequency is determined by the product of a generic frequency and certain modifying factors that are associated to the equipment, process, meteorology and management system:

$$f_{adjusted} = f_{generic} \cdot F_E \cdot F_M \quad (2)$$

where

$f_{adjusted:}$ adjusted frequency (y^{-1})

$f_{generic:}$ generic frequency (y^{-1})

$F_{E:}$ equipment modification factor (-)

$F_{M:}$ modification factor for the evaluation of the management system (-).

The equipment modification factor examines specific details for each single equipment, corrosion, complexity, stability and meteorology. The management factor has to deal with the influence of management systems of the installation.

4. Optimization Methodology Applied to Inspection

The proposed methodology is based on that previously developed for process design (Medina et al, 2009). Now, the decision variable is associated to inspection procedures, so the investment cost is given by the cost of the procedure. The objective function consists of two terms: the cost of those accidents which reasonably can occur and the cost of investing in certain procedures, both depending on the decision variable. Therefore, an important point is the estimation of costs.

4.1 Cost of an accident

The most probable/significant accidents must be identified as a function of the type of substance and the operating conditions. Then the effects of these accidents must be calculated with the appropriate mathematical models, as well as the consequences through vulnerability models and their cost.

4.2 Cost of the inspection procedure

The cost is given according to the specific type of procedure (inspection, audit.) Values of the procedure effectiveness can be applied. It is reasonable to assume that the annual cost of accidents tend to decrease as safety procedures are taken into account, while the investment cost of these procedures increases. Therefore, the solution is given by the optimization of the objective function -the sum of two terms- which may have a minimum which represents the optimal scenario.

5. Case Study

The optimization procedure can be applied effectively to the establishment of inspection plans. The number of inspections can be estimated for a given equipment or process during its lifetime. The analysis of a pipe transportation of SO_2 has been chosen as a case study. The 3 inches steel single pipe has a length of 100 m. The accident scenario considered is a continuous release of SO_2 through a hole in the pipe at a rate of 10 kg·min^{-1}, originating a toxic cloud. It is assumed that there are 5 people exposed to the gas over a period of 10 min, located at a distance of 50 m. Meteorological data are given in *Table 1*.

Table 1. Meteorological data

Wind speed ($m \cdot s^{-1}$)	4
Surface roughness (cm)	10
Cloudiness	Partly cloudy
Temperature (°C)	12
Relative humidity (%)	70

5.1 Objective function

The objective function, which is the expression of the total cost, is defined as the contribution of the cost of inspection and the cost of the accident:

$$C_T = C_I + C_{acc} \quad (3)$$

where

$C_{T:}$ total annualized cost (€ / y)

$C_{I:}$ annual inspection cost (€ / y)

$C_{acc:}$ annualized cost of the accident (€ / y).

5.2 Annualized cost of the inspection

The cost of the inspection is estimated with the equation proposed by Seider et al. (2004), which gives the annualized cost distributed over the lifetime of the equipment:

$$C_I = \frac{P_i \cdot r \cdot (1+r)^n}{(1+r)^{n+1} - 1} \cdot N_i \quad (4)$$

where

$P_{i:}$ cost of specific inspection (€)

r: interest rate in period (-)

n: equipment life time (y)

$N_{i:}$ number of inspections in the period n (-).

The cost of inspection is reported by industry as a function of the effectiveness; the cost of a fairly effectiveness inspection has been assumed here to be 150 $€ \cdot m^{-2}$. The interest rate is 0.035 and the life time of equipment is assumed to be 10 y.

5.3 Annualized cost of the accident

The cost of the accident is given by:

$$C_{acc} = f_{generic} \cdot F_M \cdot F_{E(Ni)} \cdot C_C \cdot L \cdot N_{pipes} \quad (5)$$

where

C_C: cost of consequences (€)

f: generic frequency ($m^{-1}y^{-1}$)

L: length of the pipe (m)

N_{pipes}: number of pipes (-).

For pipes, the generic frequency of a release through a hole has been taken as $2{\cdot}10^{-6}$ m^{-1} $year^{-1}$ (CPR18E, 2005). SO_2 has been assumed to have a severity index of 50. The universal, mechanical and process sub factors are considered equal to one. The accident identified is a toxic gas release through a hole. ALOHA software has been used to estimate the atmospheric dispersion of the toxic cloud. To calculate the cost of the accident originated by fatalities and injuries, the compensation values proposed by Ronza et. al. (2009) have been applied: 206,000 € for fatalities and 92,000 € for injured, which have been updated.

So, the objective function can be written as:

$$C_T = \frac{C_{insp} \cdot \pi \cdot d \cdot L \cdot N_{pipes} \cdot r \cdot (1+r)^n}{(1+r)^{n+1} - 1} \cdot N_i + f_{generic} \cdot F_M \cdot F_{E(Ni)} \cdot C_C \cdot L \cdot N_{pipes} \qquad (6)$$

where

N_i: number of inspections (decision variable).

5.4 Constraints

Many constraints are evaluated not only from a financial point of view, particularly because of the ethical and moral considerations, for example those related to human life. Therefore, some constraints related to individual risk should be taken into account. For the proposed case, the individual risk is zero since there are not any fatalities from the accident. It means that all the cases considered fulfil the tolerable risk criteria.

5.5 Optimization

Figure 1 represents the objective function in a plot of the cost as a function of the number of inspections. The inspection cost increases with the frequency of inspections, while the annual cost of the accident decreases when the number of inspections increases. However, the consequences of the accident do not vary, since neither the equipment nor the design or the components have been changed. In previous studies (Medina et al, 2009) the reduction of the cost of the accident was due to the change in the design, which involved a reduction of the consequences, while the frequency did not change. In the present case, the reduction of the cost of the accident is due to the decrease of its frequency, given by the technical sub-factor influence. For the analysed case, the minimum of the objective function corresponds to two inspections.

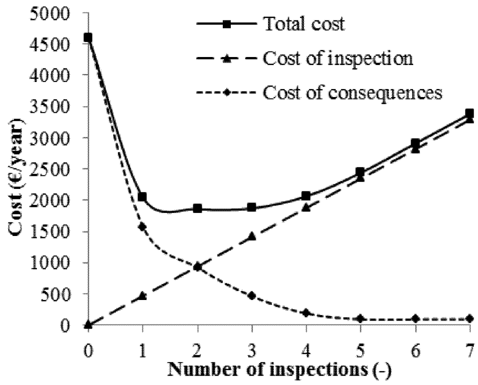

Figure 1: Sulphur dioxide pipe optimization

It is important to note that one inspection during the lifetime of the equipment reduces considerably the cost of the accidents. This highlights the need of applying this type of procedure, particularly on those processes that are highly prone to accidents.

6. Conclusions

A methodology to optimize inspection plans based on risk analysis has been proposed. The methodology allows defining an optimal number of inspections for a particular case, while taking into account the cost of the procedure and the cost of the probable accidents. In this case, the decision variable is associated with a procedure variable, the number of inspections in the life time of the equipment.

It has been shown that the cost of accidents decreases significantly when at least one inspection in the life time of the equipment is applied. The influence is more evident when the effectiveness is higher. Additionally, it has been shown that by increasing the effectiveness of the procedure the frequency of inspection can be reduced.

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