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The Management of Industrial Safety in Chemical and Petrochemical Industry by Comparing Costs and Benefits

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Chemical and petrochemical installations are complex installations, thus, for these huge efforts are needed to protect people/workers and the environment from the occurrence of major accidents. Due to this evidence, an increased attention has been paid by designers and operators in finding innovative solutions to guarantee higher levels of safety, in order to avoid that failures and losses of containment from process equipment could lead to serious consequences. To this purpose, the RBI approach is usually used to identify critical equipment where inspections will provide the highest benefit in reducing the overall risk. The application of this methodology permits a significantly reduction of maintenance costs and simultaneously the increase of plant's reliability and availability. It must be added that, in order to increase safety, also a proper selection of measures to be adopted is needed. In this work, the RBI method has been applied, by means of a recent developed tool named *Inspection Manager*, to support the selection of measures to be adopted with respect to an accidental event causing the release of hazardous materials.

1. Introduction

A relevant issue for the accident prevention is to define measure reducing risk and to quantify the safety investment. It is a common thought that increases in safety investments result in better safety performance (Abrahamsen et al., 2013); although, the positive correlation between safety investment and safety performance is easy to understand, it has been proved that the effect of safety investment on safety performance is strongly influenced by safety culture (Ma et al., 2016). An increased attention is needed from both the designers and operators' side in finding innovative solutions to guarantee higher levels of safety, otherwise failures and losses of containment from process equipment could lead to serious accidental scenarios (Palazzi et al., 2015, Vintr and Valis, 2012,). Approaches to determine optimal safety investment decisions are necessary for selecting safety measures and controlling costs for the plant management (Aven and Hiriart, 2011). Cost-benefit analysis, which is the approach widely used to analyse safety investment decisions, indicates that there is a point where and additional investment diminishing its return; according with the safety investment model, the probability of an accident is a function of the amount of investment and the optimal amount of investment is determined by minimizing total expected costs (Ma et al., 2016).
The main problem in the decision-making process is the lack of knowledge of costs related to accidents; as pointed by Gavious et al. (2009), this is due to the misunderstanding that the costs related to accidents are believed to be insured and not as part of the financial situation of the company. A common though is that these costs are limited to the direct accident costs, whereas indirect accident costs also need to be included (Adnett and Dawson, 1998). This evidence is reflected on the difficulty to measure and, thus, to correctly compare costs and benefits. In addition, it has been evidenced that cost-benefit analyses are highly time-consuming, therefore, approaches and tools supporting the process are strongly needed. Despite the availability numerous tools (Reniers and Brijs, 2014), the estimation of costs remains a time-consuming process in the chemical and petrochemical context due the collection of a lot plant-specific information. This need oriented the research towards the development of a system collecting and managing plant-specific data and its integration a tool performing cost-benefit analyses.

Recently a software, named 'Inspection Manager' and developed by ANTEA, has been implemented in order to allow the execution of the API Risk Based Inspection analysis (RBI (American Petroleum Institute, 2008). It was implemented thanks to cooperation with the University of Padova (Italy) and, during this last year, has been proposed as a tool supporting the management of operational risks and the decision-making process. The software can be easily used in developing inspection and maintenance programs as it allows taking advantage from the plant-specific data that are stored within the software's database (Vianello et al., 2013; Vianello et al., 2016).
In this work, the support of the Inspection Manager has been tested by means of its application to a case-study, which is an isomerisation unit of a petrochemical industry, in order to select measures to be adopted with respect to an accidental event causing the release of a dangerous material. After the identification of the most effective measures, a careful assessment of the costs has been executed to complete the decision-making process with a cost-benefit analysis related to the investment in safety.

2. Methodology

The methodology adopted for the selection of measure, which is implemented in the Inspection Manager software, is based on the cost-benefit analysis as proposed by the API Risk Based Inspection (RBI) document (American Petroleum Institute, 2008). The final tool has been implemented to recall the sequence of operations, as it has been schematised in Figure 1, where the most relevant processes are the RBI analysis and the cost-benefit comparison.

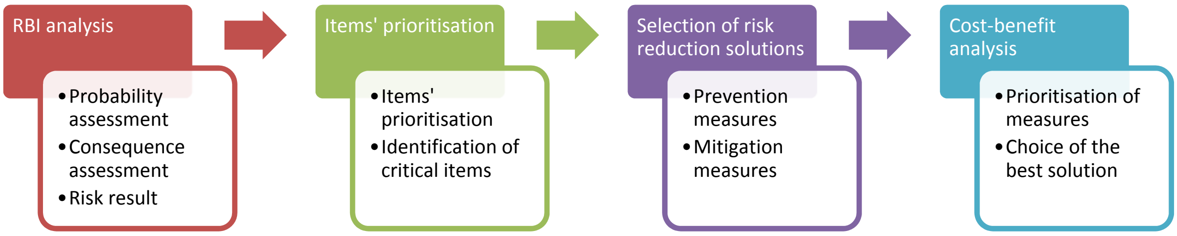

Figure 1. Flowchart to choice the best solution minimising the risk with respect to an incidental scenario

The API RBI can be used to identify critical items inside the establishment, where inspections are needed in order to provide the major benefit in reducing the overall risk. The risk calculation consists in relating the failure probability to its consequence. According to the API RBI guidelines, the risk calculation involves the determination of a probability of failure (P), which has to be combined with the consequence extension of following scenario (C), that are expressed as impact areas and financial costs. The methodologies to calculate the probability of failure are described in the document RBI 581 (American Petroleum Institute, 2008).

2.1 Consequence areas

Consequences are calculated by using a simplified procedure based on empirical equations for a predefined set of hole sizes that reflects the range of possible outcomes (Vianello et al., 2014). Methods for the dispersion modelling quantify the extent and duration of personnel exposure; these allow correcting the release characteristics based on the adoption of detection, isolation and mitigation systems. These systems affect the release in several modes, i.e. by reducing its magnitude and duration, by detecting and isolating the leak or by reducing the consequence area through the minimisation of the chances for ignition or limiting the spread of material (see document RBI 581, American Petroleum Institute, 2008).

2.2 Financial consequence

As proposed by Gavoius et al. (2009), the reliable evaluation of the cost of industrial accidents can help managers and workers to internalise the importance of safety measures and consider investments to promote the safety. A model for the estimation of the total cost of an industrial accident has been proposed by these authors; its general structure is given by equation (1), where the total cost is the sum of direct costs (C_{direct}), indirect costs ($C_{indirect}$), other payments ($C_{payment}$) and immeasurable costs ($C_{immeasurable}$).

$$C_{total} = C_{direct} + C_{indirect} + C_{payment} + C_{immeasurable} \tag{1}$$

Table 1: Cost classification (Gavoius et al., 2009)

Direct cost	Indirect costs
C_{damage}: Costs due to the damage of products, equipment and machinery.	$C_{capacity\ lost}$: Costs resulting from the capacity loss (slowdown or halt).
$C_{medical}$: Costs due to medical treatment costs (evacuation to the hospital, payment for treatment given the accident, hospitalisation, etc.).	$C_{schedule}$: Costs resulting from the not respect of the timetable schedule that causes damages to the client (clients cancel the contract or demand for a lower price).
C_{fine}: Costs due to fines that have to be paid if an accident is caused by violations of safety procedures or of the law.	$C_{recruit}$: Cost due to the hiring additional workers to replace the injured ones, it includes the time invested in recruiting and training the new workers.
$C_{insurance}$: Costs due to the annual payment for an insurance premium. This varies over the years if events occurred in the previous year	$C_{work\ time}$: Costs due to the time spent in other needs due to the accident (e.g. managers have to invest in investigating the accident).
	C_{wip}: Costs due to the bottleneck created by the accident (e.g. the inventory starts to grow and accordingly the cost connected to it grows as well).
	C_{mang}: Costs connected with the CEO time payment.

The cost for payment ($C_{payment}$) has to be considered in case of refund, it quantification is given by Gavoius et al. (2009). Immeasurable costs ($C_{immeasurable}$) are due to the lost reputation for the company and the impact on the morale of workers, models for their assessment are not well-consolidated.
The API methodology contains elements that make it able to determine financial consequences. By comparing the model of Gavoius et al. (2009) and the API approach (Table 2), it has been observed that:

(i) the cost for equipment repair/replacement and that for the environmental clean-up are both included in the cost for damage of Gavious and co-workers;
(ii) costs for production losses and business interruption includes four cost types of Gavious et al., i.e. those due to capacity lost, not respected production schedule, the recruitment of additional workers and the bottleneck created by the accident;
(iii) the API model does not include the cost for fine, insurance and for the CEO time payment.

Table 2: Cost classification (API document)

Cost	Description
FC_{CMD}	Cost for equipment repair and replacement
FC_{ENV}	Cost for environmental clean-up
FC_{INJ}	Cost due to potential injuries associated with failure
Not included	Cost for fines
Not included	Cost for insurance
FC_{PROD}	Costs associated with production losses and business interruption
FC_{INJ}	Cost due accident investigation
Not included	Costs for the CEO time payment
Not included	Refund
FC_{INJ}	Cost due loss reputation

The following section describes a case-study which has been used to compare the approach of Gavoius et al. (2009) and that included in the API standard.

3. Case study: Desulphurisation reactor of an isomerisation plant

The case-study is a desulphurisation reactor of an isomerisation plant. The analysis has been focused on the desulphurization reactor, whose characteristics are shown in Table 3. The substances that are treated are light hydrocarbon (C6 - C8) and hydrogen.
By means of the application of the Inspection Manager, the following damage mechanisms have been highlighted in the reactor:

- corrosion under insulation (CUIF)
- thinning (THIN) – high temperature H_2/H_2S corrosion

Table 3: Desulphurisation reactor characteristics

Data	Value	Data	Value
Diameter [mm]	1100	Insulation type	Mineral wool
Length [mm]	2540	Installation equipment data	1997
Furnished thickness [mm]	18	Data of last inspection	2007
Operating Pressure [barg]	28.5	Level of inspection effectiveness	Usually effective
Operating Temperature [°C]	270-290	Corrosion allowance [mm]	1.5
Design Pressure [barg]	34	Coating installation	1997
Design Temperature [°C]	350	Coating quality	Medium
Material	1.25%Cr - 0.5%Mo	Insulation conditions	Average

The management system factor is an adjustment factor that accounts for the influence of management system on the mechanical integrity of the plant equipment. It is indicative of the quality of facility's mechanical integrity and the process safety management programs (Milazzo et al., 2013). In this work, the analysis has been conducted for two different values of *management system factor (FMS)*:

- a high value that corresponds to a score of 1000 and it equates to achieving excellence in process safety management issue;
- a low value that corresponds to a score of 500 and it corresponds to average level in process safety management.

A low value of the *managerial system factor* can lead to inefficient safety management and thus create a predisposition to gaps and errors that can increase the likelihood of an incidental event. The generic failure frequency of reactor is equal to $3.06 \cdot 10^{-5}$ event/year (data from the Safety Report).

4. Results

The probabilities of failure, calculated by considering *damage and management system factors*, are summarised in Table 4Table 4.. It can be seen that the management system of the plant changes the probability of occurrence of the event, the greater the efficiency of the managerial system the less likely the damage will occur.

Table 4. Probabilities of the event for the two values of management system factor

Management system factor	FMS	P [failure/years]	Probability Category
High value	0.1	$3.33 \cdot 10^{-6}$	1
Low value	1	$3.33 \cdot 10^{-5}$	2

4.1 Consequence Impact area

Different cases have been investigated to understand how detection, isolation and mitigation systems can affect consequence impact areas. Case 1 represents the absence of prevention and mitigation systems, this means that the release if not reduced. In Case 4, detection, isolation and mitigation systems have a high influence on the consequence of the event. From Case 1 to Case 4, the adoption of safety measures increases as well as the *adjustment factor*, thus the effect is an increasing reduction of the magnitude and duration of the release. Results are expressed as component damage consequence (CMD) and injury consequence (INJ), with respect to the different threshold limits of consequences taken from the API document. A reduction of the extension of consequence impact areas can be observed due to increasing quality of detection, isolation and mitigation systems.

Table 5. Consequence results

Consequence	Case 1	Case 2	Case 3	Case 4
Component Damage Consequence - CMD [m^2]	122.90	112.35	90.04	75.63
Injury consequence - INJ [m^2]	356.15	326.56	262.23	221.24
Final consequence - CA = max(CMD, INJ) [m^2]	356.15	326.56	262.23	221.24

4.2 Financial consequences

The API methodology includes the determination of the financial consequences, moreover considers several costs related to the component damage, the business of interruption, people involved in the accident (injuries)

and the environmental damage. This means that, as already evidenced by the literature (Gavoius et al., 2016), the analysis of costs needs the collection of a great amount of data.
To calculate the cost for equipment repair or replacement (FC_{CMD}), the equipment is needed. It was estimated as proposed by Towler and Sinnott (2013) and is estimated to be 133,400 \$. The FC_{CMD} is given by the following terms: the cost of the damaged component, the cost of the equipment's material and the cost to surrounding equipment in affected area (FC_{AFFA}), calculated using equation:

$$FC_{AFA}=CA_{CMD}\cdot equipment\ cost \quad (2)$$

where CA_{CMD} is the component damage consequence.
The cost associated with the production losses and business interruption (FC_{PROD}) includes the quantification of the costs due to the loss of product caused by the accident and to the shutdown of the facility, needed to repair the damage of the equipment. The cost of business interruption, associated with the repairing damage equipment, is equal to the cost associated with lost production due to shutdown facility. To identify such a value, it is necessary to determine the product cost. By assuming a product capacity for the plant equal to 100,000 bbl/day and the material cost of 8 \$/bbl (Garrett, 1989; US EIA website), the estimated cost is 800,000 \$/day.
The cost due to potential injuries associated with the failure includes the following:

- Local medical/compensation costs associated with long-term disability,
- Legal/settlement costs,
- Indirect costs such as increased regulatory scrutiny, loss of reputation, etc.

This value must be sufficiently high to adequately represent typical costs of an injury up to and including fatal injuries. As proposed by the “HSE cost to Britain Moddel” website, the estimated cost of potential injuries and ill health is equal to 2.2 Million \$.
The last cost is that associated with the environmental cleanup. The value proposed by Riutenbeek (2013) for a spill from pipeline or equipment is estimated equal to 1 ÷ 8 Million \$. For the case study, the environmental clean-up cost is appraised to be equal to 2 Million \$.
Due to the lack of data related to the cost for mitigation, isolation and detection systems, the analysis was conducted by assigning a score to each case study, which rises with the increase of costs for the acquisition of the measures. A score equal to 0 has been assigned to systems that do not contribute in reducing the consequences (e.g. Case 1), while a score of 10 has been given to measures that effectively contribute to the reduction of the impact area as in Case 4.
By analysing results related to financial consequences and the scores for safety measures, as shown in Figure 2. It can be seen that, as the efficiency of the mitigation, isolation and detection systems increases, the costs due to an incident decrease. The graph also shows that it is possible to identify a point that represents a compromise between the investment to improve the safety, by means of the adoption of measures systems, and the costs incurred due the occurrence of the accident.

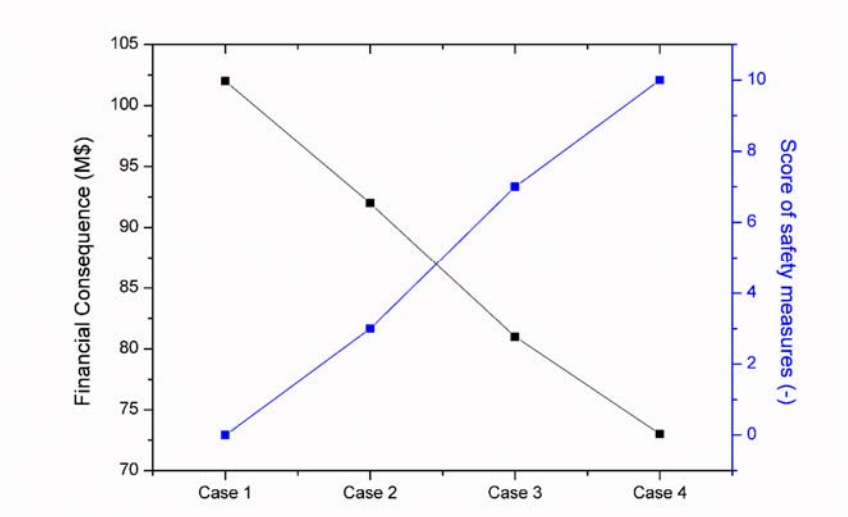

Figure 2. Financial consequences versus score of safety measures

5. Conclusions

The implementation of the *Inspection Manager* software, proposed in this work, supports performing cost-benefit analyses, already made by other numerous existing tools; in addition it allows to further simplifying the work of the industrial manager through a simple management of plant-specific data, which is not feasible with other tools. The use of the *Inspection Manager* has also allowed a comparison between the methods for estimating costs for accidents, proposed in the API 581 document and in the work of Gavious et al. (2009), this has shown some differences not yet resolved among the various models. In case of the models examined, the main differences are related to the quantification of costs fine, insurance and for the CEO time payment.
Concerning the case study, it has been observed that the use of the *Inspection Manager* tool, as a support to the decisions, allows to obtain numerous benefits: (i) the quantification of the financial consequences for the accident by using plant-specific data in a simpler and faster way; (ii) the guided-execution of the analysis and, (iii) the comparison between financial consequences and the scores for safety measures, which allows identifying a point that represents a compromise between the investment to improve the safety, by means of the adoption of measures systems, and the costs incurred due the occurrence of the accident.

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