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Managing Industrial Safety through a Cost-Benefit Approach: a Case Study

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The safety management of chemical and petrochemical installations is a complex issue. Plant managers have continuously to search for innovative solutions dealing with the prevention of failures and losses of containment from process equipment. To this scope a great support is given by popular standards, i.e. API Risk Based Inspection (RBI) that permits a significant reduction of maintenance costs and, at the same time, the increase of plant's reliability and availability. To support these activities, a software, named *Inspection Manager*, has been developed in these last year; it allows defining inspection and maintenance programs as it takes advantage from plant-specific data stored in the database. The use of this tool permits a significantly reduction of maintenance costs and, simultaneously, the increase of plant's reliability and availability. Given that, in the context of chemical industry, a proper selection of measures is needed to increase the level of industrial safety and that the adoption of such measures poses costs, a more recent version of *Inspection Manager* has been integrated by a tool supporting cost-benefit analyses. This paper presents a case-study, which allows a further testing of the functionality of the *Inspection Manager* tool by using a more complex context compared to the past applications. The case-study is an absorption unit of a refinery, after the identification of the most effective measures, a careful cost-benefit assessment has been executed as a basis for decision-making.

1. Introduction

Establishments at major hazard include activities characterised by a considerable level of risk, regarding the large potential for accidents deriving from the loss of control of chemical processes and/or the handling of substances (Palazzi et al., 2017; Fabiano et al., 2017). These activities could lead to the release of hazardous materials and are regulated by the Seveso Directives. Due to this potential, chemical plants are complex systems to be managed, hence performance have to be monitored to avoid major accidents; this can be done by collecting plant data that are continuously verified by control systems (i.e. process variables) (Alhéritière et al., 1998) and/or during inspections (i.e. equipment integrity) (Vintr and Valis, 2007; Bragatto and Milazzo, 2016; Valis et al., 2015). Additionally, plant operators have to adopt proper measures for risk reduction (AlKazimi & Grantham, 2015; Vianello et al., 2018); this latter point requires further efforts because, even if increases in safety investments should result in better safety performance for the plant, economical resources for the company in most cases could be limited (Abrahamsen et al., 2018).
In general, safety investments aim reducing the accident probability and injuries, but it must be recalled that the effect of safety investment on safety performance is strongly influenced by safety culture (Ma et al., 2016). In addition, the decision process for the selection of safety measures requires articulated approaches that involves a number of actors (Aven and Hiriart, 2011). Cost-benefit analysis is the approach widely used to support decisions (Reniers & Bris, 2014a) given the easiness in the interpretation of results, even if it a time-consuming method. Based on 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 minimising total expected costs (Ma et al., 2016); the model also indicates that there is a point where and additional investment diminishing its return. Unfortunately, the main problem in dealing with cost-benefit analysis is the lack of knowledge about costs of accidents; this is due to the misunderstanding that these are believed to be insured and not as part of

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the financial situation of the company (Gavious et al., 2009). Thus, costs of accidents are limited to the direct costs whereas, as pointed by Adnett & Dawson (1998), indirect accident costs should also be included in order to correctly compare costs and benefits. Given that cost-benefit analyses are highly time-consuming, numerous approaches and tools supporting the process have been developed (Reniers and Brijs, 2014b), especially in the chemical and petrochemical industry. To this purpose, a recent developed tool is the software *Inspection Manager*, developed by ANTEA and implemented during a cooperation with the University of Padova (Vianello et al, 2013). It can be easily used to define inspection and maintenance programs, based on Risk Based Inspection analysis RBI (American Petroleum Institute, 2016) and taking advantage from the plant-specific data that are stored in the database (Vianello et al., 2016). Furthermore, a more recent version allows supporting cost-benefit analyses by means of a proper module (Vianello et al., in press).

This paper presents a further validation of the last version of the software *Inspection Manager*. Compared with the previous testing (Vianello et al., 2018), a more complex case-study has been used to apply the cost-benefit analysis for the selection of some risk reduction measures or to proceed with their replacement with others that. The case-study is an absorption unit of a refinery, where hydrogen is purified at high level of purity.

2. Methodology

To understand if an investment is an efficient use of the resources of company, a comparison costs and benefits has to be carried out. In the context analysed by this paper, i.e. the safety management in chemical industry, the investment refers to safety measures; therefore. a cost-benefit analysis support in understanding the level of distribution of benefits and costs associated to the investment in selected safety measures. This information helps the plant operator in decision-making.

The approach of cost-benefit analysis has been integrated by Vianello et al. (2018) as a further module in the software *Inspection Manager*; it is based on criteria proposed by the API Risk Based Inspection (RBI) document (American Petroleum Institute, 2008), which are schematised in the Figure 1. However, the software support the comparison also with other models that have been proposed for cost-benefit analysis.

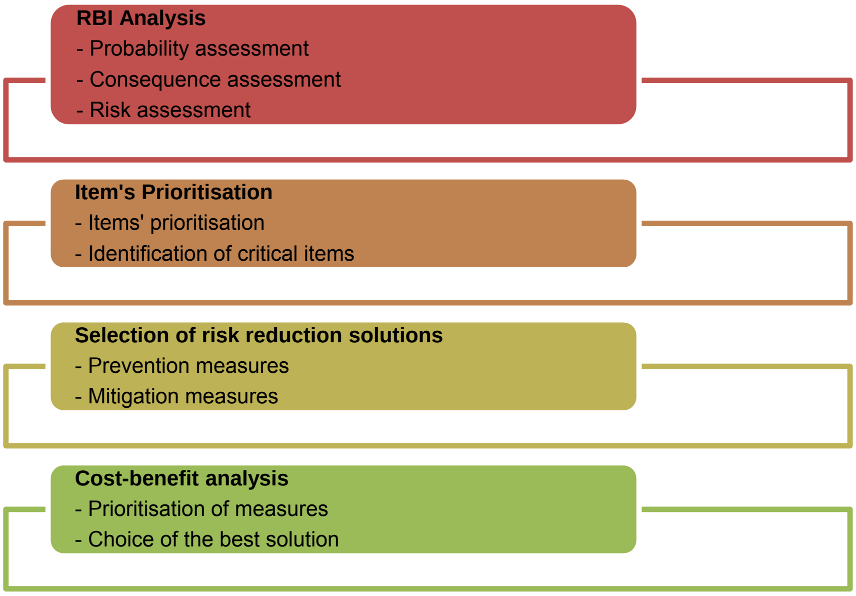

Figure 1. Steps of the methodology implemented in the Inspection Manager software (American Petroleum Institute, 2008).

2.1 Cost-benefit analysis

The cost and benefit analysis is a time-consuming procedure because it requires the collection of a large amount of data. To perform this analysis, different models are available, such as the RBI methodology and the model proposed by Gavoius et al. (2009). A comparison between the methods has been made by Vianello et al. (2018, in press) to highlight how to improve the conduction of the analysis by the support of the *Inspection Manager* software. A summary of the differences identified by comparing the models is given in Table 1.

The general model for the quantification of cost is given by the following equation:

$$C_{total} = C_{direct} + C_{indirect} + C_{payment} + C_{immeasurable} \quad (1)$$

where the total cost is the sum of direct costs (C_{direct}), indirect costs ($C_{indirect}$), other payments ($C_{payment}$) and immeasurable costs ($C_{immeasurable}$).
The details about the calculation of each single factor has not been given in this contribution as it is widely reported in the literature (Gavious et al., 2009, American Petroleum Institute, 2016).

Table 1. Comparison between models for cost estimation

Model of Gavoius et al.	API 581 model	Description
C_{damage}	FC_{CMD}, FC_{AFFA}	Cost for equipment repair and replacement
	FC_{ENV}	Cost for environmental clean-up
$C_{medical}$	FC_{INJ}	Cost due to potential injuries associated with failure
C_{fine}	Not included	Cost for fines
$C_{insurance}$	Not included	Cost for insurance
$C_{capacity\ lost}$, $C_{schedule}$, $C_{recruit}$, C_{wip}	FC_{PROD}	Costs associated with production losses and business interruption
$C_{work\ time}$	FC_{INJ}	Cost due accident investigation
C_{mang}	Not included	Costs for the CEO time payment
$C_{payment}$	Not included	Refund
$C_{immeasurable}$	FC_{INJ}	Cost due loss reputation

3. Case-study

The information that allows the conduction of the RBI assessment for the case-study, as well as the cost-benefit analysis, have been stored in the *Inspection Manager*. The analysis has been applied to process of production of hydrogen with a high purity of a refinery, which is summarised in Figure 2. In particular, the focus of the analysis has been on the hydrogen separation unit (PSA), in which high purity hydrogen (> 99.5%) is obtained by separating impurities with six columns of adsorption. The columns are subsequently regenerated by reducing the pressure with the consequent desorption of the impurities. The separated off-gas is used as the primary fuel in the reforming section. The characteristics of the column are shown in Table 2.

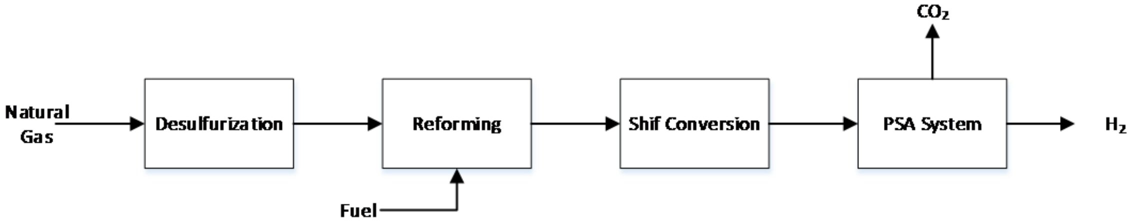

Figure 2 Block diagram

Table 2. Absorption column characteristics

Data	Value	Data	Value
Diameter [mm]	1650	Material	Carbon steel (A516)
Length [mm]	5190	Installation equipment data	1997
Furnished thickness [mm]	20	Data of last inspection	2010
Operating Pressure [barg]	23	Level of inspection effectiveness	Usually effective
Operating Temperature [°C]	40	Corrosion allowance [mm]	3
Design Pressure [barg]	26	External environmental	Temperate
Design Temperature [°C]	100	Intial fluid phase	gas

By means of the *Inspection Manager*, the following damage mechanisms have been highlighted for the columns: external corrosion and thinning damage. These are necessary to modify the generic frequency of failure of the equipment by means of a proper factor for the deterioration mechanism.
A managerial factor has also to be included in order to take into account the influence the management system (Milazzo et al., 2013). Two values for this factor have been accounted for to quantify its influence on the calculation of the event probability:

- the high value (score = 1000) equates to achieve excellence in process safety management;
- the low value (score = 500) corresponds to an average level in process safety management.

Given that hydrogen is a highly flammable substance, the incidental scenarios that follow the release, due to the equipment failure, are a fire and an explosion. The consequence assessment has been done according to the empirical equations of (American Petroleum Institute, 2008). The release modelling quantifies the extent and duration of the flammable dispersion; these parameters are corrected based on the adoption of detection, isolation and mitigation systems. These 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.

In consequence assessment, the six columns are considered to contain the maximum quantity that can be inventoried in the equipment and the whole system has been considered a single circuit. To make a comparison between costs and benefits associated with the equipment repair or replacement after the accident, several data are needed, some of them are given in Table 3.

Table 3. Cost for financial analysis

Cost	Value	Reference
Equipment [$]	11,863	Towler and Sinnott, 2013
Lost production [$/day]	992,300	Ramsden et al., 2007
Serious injury of fatality of personnel [$]	2,200,000	HSE cost to Britain Moddel
Environmental clean-up [$/m^3]	680,000	Métivier et al., 2017; Ramsden et al., 2007

To carry out a financial analysis, the equipment cost is evaluated with the correlation proposed by Towler and Sinnott (2013); the cost associated with the production losses and business interruption is quantified to the cost associated with lost production due to shutdown facility and then it is necessary determine the product cost. By assuming a product capacity for the plant equal to 100,000 Nm^3/h and a material cost of 4.6 $/kg for H_2 (Ramsden et al., 2007), the estimated cost is 992,300 $/day. 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 $.

Given that the released substance is in gas phase, there is not a direct environmental contamination due to a liquid spill. Nevertheless, hydrogen contributes to the environmental impact as it is a greenhouse gas, for this reason the cost associated with environmental cleaning has been considered in term of cost deriving from the equivalent CO_2 emissions due to the hydrogen production plant (Métivier et al., 2017; Ramsden et al., 2007).

4. Results

The generic failure frequency of the column is equal to $3.06 \cdot 10^{-5}$ event/year (data from the Safety Report). The resulting damage factor (FMS) and probabilities of failure, calculated by considering damage and management system factors, are summarised in Table 4.

Table 4. Probabilities of the event for the case study

Management system factor	Total Damage factor	FMS	P [failure/years]	Probability Category
High value	3	0.1	$9.18 \cdot 10^{-6}$	1
Low value	3	1	$9{,}18 \cdot 10^{-5}$	2

To define how prevention and protection measures act, several cases have been studied: case 1 represents the absence of prevention and mitigation systems; case 4 represents the greatest influence on the consequences by detection, isolation and mitigation system; from case 1 to case 4, the adoption of safety measures as the effect of an increasing reduction in magnitude and duration of release. According to the RBI methodology, the results are expressed as a consequence of the damage to the equipment (CMD) and consequently on the people (INJ), in relation to the different threshold limits (Table 4). Figure 3 shows a visual representation of the consequence results CMD (see Table 5) by means of risk matrixes.

Table 6 shows the result of the financial consequences analysis for cases 1 ÷ 4. It can be observed that the increased reduction of the release by means of the safety measures reduces the financial costs due to the accident. By considering only the cost of the installation of the mitigation systems, see in the Table 7 (Janssens et al., 2015), it is possible to identify a point that represents a compromise between the investment and the benefit that derive from the adoption of safety measures (Figure 4). This is a valid support in make decisions aimed at the improved of safety.

Table 5. Consequence results

Consequence	Case 1	Case 2	Case 3	Case 4
Component Damage Consequence - CMD [m^2]	65.14	44.80	36.23	30.97
Injury consequence - INJ [m^2]	310.98	152.83	123.78	105.49
Final consequence - CA = max(CMD, INJ) [m^2]	310.98	152.83	123.78	105.49

Table 6. Financial consequence results

	Case 1	Case 2	Case 3	Case 4
Financial consequence [M$]	27.60	21.57	20.07	19.08

Table 7. Mitigation systems cost

System	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Mitigation	fire water monitoring only	fire water monitoring only	fire water deluge system and monitoring	Inventory blowdown, coupled with isolation system activated directly from process instrumentation or detectors or by operator in the control room
Cost K$	25	25	200	500

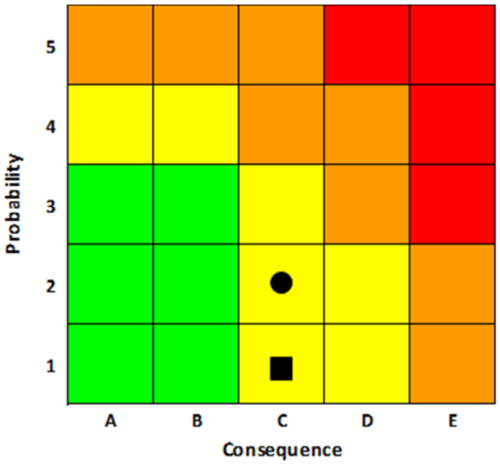

Figure 3 Risk matrix: (●) low value of management system factor, (■) high value of management system factor.

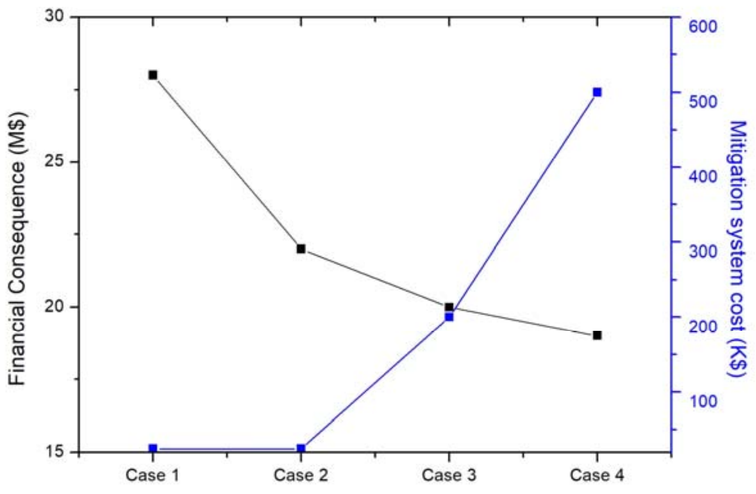

Figure 4 Financial consequences versus mitigation system costs.

5. Conclusions

The use of the *Inspection Manager* software, integrated with a tool for cost-benefit analysis, supports the analysis of complex case-studies because it allows simplifying the work of the industrial manager through a simple management of plant-specific data. Concerning the case study, the following benefits derive from the use of the tool, these are related to: the quantification of the financial consequences for the accident by using different methodologies and the comparison between financial consequences, derived from different safety measures and safety management system. The comparison allows identifying the point that represents a compromise between the investment to improve the safety and investment.

References

Alhéritière, C., Thornhill N.F., Fraser S., Knight M.J., 1998, Cost Benefit Analysis of Refinery Process, Computers & Chemical Engineering, 22(1), S1031-S1034.

Abrahamsen E.B., Moharamzadeh A., Abrahamsen H.B., Asche F., Heide B., Milazzo M.F., 2018, Are too many safety measures crowding each other out?, Reliability Engineering and System Safety, 174, 108-113.

American Petroleum Institute, 2008, Document API RP 581 Risk-Based Inspection Technology, Second Edition.

Aven T., Hiriart Y., 2011, The use of a basic safety investment model in a practical risk management context, Reliability Engineering &. System Safety, 96(11), 1421–1425.

Bragatto P., Milazzo M.F., 2016, Risk due to the ageing of equipment: Assessment and management, Chemical Engineering Transactions, 53, 253-258.

Fabiano B., Vianello C., Reverberi A.P., Lunghi E., Maschio G., 2017, A perspective on Seveso accident based on cause-consequences analysis by three different methods, Journal of Loss Prevention in the Process Industries, 49(A), 18-35

Gavious A., Mizrahi S., Shani Y., Minchuk Y., 2009, The costs of industrial accidents for the organization: Developing methods and tools for evaluation and cost-benefit analysis of investment in safety, Journal of Loss Prevention in the Process Industries, 22, 434–438.

Janssens, J., Talarico, L., Sörensen, K., 2015. A decision model to allocate protective safety barriers and mitigate domino effects. Reliab. Eng. Syst. Saf. 143, 44–52. doi:10.1016/J.RESS.2015.05.022

Ma Y., Zhao Q., Xi M., 2016, Decision-makings in safety investment: An opportunity cost perspective, Safety Science, 83, 31–39.

Métivier, C., Postic, S., Alberola, E., Vinnakota, M., 2017. Global panorama of carbon prices in 2017. Paris.

Milazzo, M.F., Vianello, C., Maschio, G., Mura, A., 2013. The frequency of release from piping: A case-study to compare approaches quantifying organizational and managerial factors. Chem. Eng. Trans. 32, 127–132.

Palazzi E., Caviglione C., Reverberi A.P., Fabiano B., 2017, A short-cut analytical model of hydrocarbon pool fire of different geometries, with enhanced view factor evaluation, Process Safety and Environmental Protection, 110, 89-101.

Ramsden, T., Ruth, M., Diakov, V., Laffen, M., Timbario, T.A., 2007. Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios.

Reniers G., Brijs T., 2014a, Major accident management in the process industry: An expert tool called CESMA for intelligent allocation of prevention investments, Process Safety and Environmental Protection, 92, 779-788.

Reniers G.L.L., Brijs T., 2014b. An Overview of Cost-benefit Models/Tools for Investigating Occupational Accidents, Chemical Engineering Transactions, 36, 43–48.

Vianello C., Maschio G., Mura A., Babolin, D., Gambato F., Attori C., 2013, Development of a RBI tool for inspection management in chemical plants, Chemical Engineering Transactions, 31, 235-240.

Vianello C., Milazzo M.F., Guerrini L., Mura A., Maschio G., 2016, A risk-based tool to support the inspection management in chemical plants, Journal of Loss Prevention in the Process Industries, 41, 154-168.

Vianello C., Milazzo M.F., Maschio G., 2018, The management of industrial safety in chemical and petrochemical industry by comparing costs and benefits, Chemical Engineering Transactions, 67.

Vianello C., Milazzo M.F., Maschio G., in press, Cost–benefit analysis approach for the management of industrial safety in chemical and petrochemical industry, Journal of Loss Prevention in the Process Industries.

Vališ, D., Žák, L., Pokora, O., 2015, Failure prediction of diesel engine based on occurrence of selected wear particles in oil, Engineering Failure Analysis 56, 501-511

Vintr Z., Valis D., 2007, Modeling and analysis of the reliability of systems with one-shot items, Proceedings of the 53rd Annual Reliability and Maintainability Symposium (RAMS), p. 380.