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Innovative LOPA-Based Methodology for the Safety Assessment of Chemical Plants

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The aim of the present work was the development and application of a methodology for the safety assessment of chemical plants based on LOPA (Layer of Protection Analysis) techniques.
The approach integrates the use of consolidate hazard identification techniques (HazOp) and the adoption of quantitative literature models for consequence assessment (e.g., integral models) into the LOPA framework, allowing to limit the role played by expert judgment in the evaluation in order to reduce the causes of uncertainty in the results. Furthermore, a systematic and quantitative assessment of safety measures contribution to the reduction of plant residual risk was included in the analysis.
In order to apply the methodology, a case study was defined taking into account an actual industrial facility. The results obtained allowed demonstrating the potentialities of the method.

1. Introduction

Process industry activities go hand in hand with major hazard potential that occasionally results in major accidents (Mannan, 2005). Hence, adequate management and control of such major hazards is essential to guarantee a long-term license to operate (Pasman and Reniers, 2014). In Europe, the implementation of a policy for control of major hazards involving chemical substances is regulated via the so-called Seveso legislation. Seveso directive 96/82/EC (EC, 1997) proposed a classification of installations based on the type and quantity of hazardous substances in order to identify those where the risk of a major accident occurrence is significant (Tugnoli et al., 2012a). The installations that fall under the obligations of Seveso directive are compelled to produce a safety report, in which the results of the plant risk analysis, together with the implemented safety measures, have to be detailed. The methodologies adopted in the preparation of safety report are well-known (Tugnoli et al., 2012b) but they require a considerable cost effort (mainly in terms of man-months needed) that are currently decreasing by the use of dedicated software (Cozzani et al., 2014).
In the specific framework of chemical industries, an alternative methodology is currently becoming more diffused and applied: Layer of Protection Analysis – LOPA (CCPS, 2001). LOPA is very popular and widely utilized, because it fits perfectly with the advent of risk-based engineering standards, such as IEC 61511, specifying SIL (Safety Integrity Level) of Safety Instrumented Systems for reducing various categories of risk to a tolerable value (De Rademaeker et al., 2014).
LOPA methodology is based on a simplified risk assessment, that integrates evaluations on the inherent hazard associated with hazardous materials (Cordella et al., 2009) and process operations (Tugnoli et al., 2007) with issues related to the availability and efficiency of safety systems and/or maintenance policies focused on safety (Dowell, 1997).
In the present work, a LOPA based methodology is developed in order to obtain an innovative simplified risk assessment tool specific for chemical industry installations. In particular, the methodology allows to establish whether the protection systems and prevention/mitigation measures implemented in a chemical site are sufficient to guarantee an acceptable level of residual risk. The application to an industrial case study is presented in order to test the potentialities of the method.

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2. Methodology

According to law prescriptions, the risk analysis to be applied to Seveso installations has to follow a step-wise procedure (EC, 1997). Preliminarily, all accidental events that may occur involving a significant release of hazardous substances have to be identified and their possible causes investigated. Next, the calculation of the frequency of occurrence and expected damages associated to the identified accidental events should be performed. Finally, the risk assessment and evaluation has to be carried out.

The same framework was taken into account for the development of the novel LOPA-based method, whose steps are illustrated in Figure 1.

As shown in Figure 1, the assessment procedure mainly grounds on concepts borrowed by the conventional LOPA technique (CCPS, 2001). Three main improvements were applied to the typical LOPA method:

1. A systematic scenario identification method was introduced (step 2), based on consolidate hazard identification techniques (HazOp).
2. A more objective consequence evaluation was considered (step 3), based on the application of integral models for the evaluation of physical effects associated to accidental scenarios (Van Der Bosh and Weterings, 1997).
3. The possibility of assigning credit factors to specific maintenance procedures and safety training was explicitly considered (step 4).

It is worth to remark that the present methodology, exactly as the LOPA quantitative assessment, considers the cause-accident-consequence combinations one by one. Hence, hereafter the term "scenario" will identify a single combination of accident cause and accident effect.

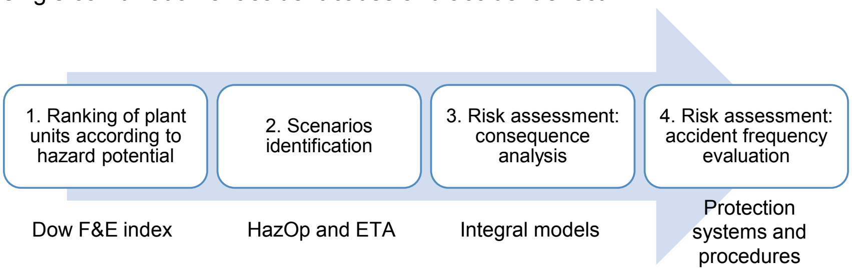

Figure 1: Methodology overview

2.1 Hazard identification

The adoption of LOPA requires a preliminary phase, supported by qualitative techniques, aimed at the identification of foreseeable accidental events. This phase is usually conducted by means of poorly structured approaches or past accident analysis.

On the contrary, in the present study the Dow Fire & Explosion Index method (Dow Company, 1987), prescribed by SEVESO directive as a support tool for safety reports development, was proposed to divide the overall plant in pertinent process units and then rank them according to their hazard potential (step 1 in Figure 1).

Next, a HazOp (Hazard and Operability) analysis was selected to the purpose of identifying the relevant accident events that might occur in the plant (step 1 in Figure 2). HazOp is a qualitative but systematic technique that analyses the deviations of process variables from normal operating conditions, in order to reconstruct cause-consequence chains related to the specific deviation (Mannan, 2005). Through the adoption of a systematic brainstorming technique by a multi-disciplinary team of experts, the risk of neglecting some relevant scenarios can be minimized in order to support consequence analysis in step 3. Event tree analysis (ETA) is then used to identify the relevant final outcomes (e.g., fires, explosions and toxic dispersions) associated to accident events.

2.2 Consequence analysis and "target factor" evaluation

Once the set of foreseeable final outcomes associated to the release scenarios has been determined, LOPA technique requires a consequences assessment phase, during which the magnitude of consequences is taken into account by means of a penalty score, namely "target factor" *TF*. The value to be attributed to *TF* increases as the severity of the accident impact on workers and population increases; however, the *TF* is often estimated according to expert judgment (CCPS, 2001) rather than on a sound objective basis.

In the present study, the evaluation of *TF* was based on the results of detailed consequence evaluation through the use of quantitative integral models (Van Der Bosh and Weterings, 1997), in order to prevent the underestimation of the severity of accidents due to the adoption of rules-of-thumb (e.g. arbitrary physical effects thresholds and arguable score attribution).

Integral models allowed to evaluate the magnitude of physical effects deriving from accident releases at different location on the site map. The model outputs in terms of heat flux, overpressure and toxic concentration were analysed by comparison against the lethality thresholds reported in Table 1 in order to quantify the expected number of fatalities, considering the number of exposed workers and the population density in the plant surroundings.

Table 1: Threshold values assumed for damage distance evaluation (LFL: lower flammability limit; IDLH: toxic concentration immediately dangerous to life and health) (adapted from Tugnoli et al., 2007).

Physical effect	Threshold Value
Flash Fire	1/2 LFL
Thermal radiation (pool fire, jet fire, fireball)	7 kW/m^2
Vapour cloud explosion	14 kPa
Physical/mechanical explosion	14 kPa
Toxic exposure	IDLH

Table 2 summarizes the scoring criteria adopted in the evaluation of TF. As it can be seen from Table 2, the involvement of people outside the plant boundaries is deemed as more critical and lead to the attribution of a higher penalty since plant personnel is usually trained to manage emergency situations.
The target factor represents the first risk estimate, which is purely based on expected damage to people as calculated through consequence analysis.

Table 2: Scoring criteria for target factor evaluation (adapted from (CCPS, 2001))

TF value	Effects on workers	Effects on population
2 - 4	Minor injury	Safe condition
3 - 5	Irreversible damage	Evacuation possibly needed
4 - 6	1 – 3 fatalities	Irreversible damage
5 - 7	3 – 10 fatalities	1 – 3 fatalities
6 - 8	10 – 50 fatalities	3 – 10 fatalities
7 - 9	50 – 200 fatalities	10 – 50 fatalities
8 - 10	More than 200 fatalities	50 – 200 fatalities

2.3 Credit factors evaluation and residual risk calculation

According to the LOPA methodology, the target factor evaluation step is followed by the definition and evaluation of a set of compensation factors. In such a phase, credits are attributed to consider the credibility of the accidental scenario and the availability of independent protection layers (IPLs), thus modifying the first risk estimate obtained according to the procedure described in Section 2.2.
The credibility is assessed as a function of the expected frequency of occurrence of the initiating cause and considering the presence of accident triggers and other aspects that may affect the final probability of occurrence of the scenario. Three different credit factors are defined to the purpose.
First, all the possible initiating causes of the release scenarios identified through HazOp analysis have to be determined. Initiating causes may include process deviations, components malfunctioning, leakages, human errors and external causes such as domino effect (Di Padova et al., 2011) or natural events - NaTech (Salzano et al., 2009). Clearly enough, initiating cause may be very different in nature and thus their frequency of occurrence may vary considerably; hence, each initiating cause-release event pair has to be analyzed independently as a “scenario”.
Next, the frequency of occurrence of the initiating event f (events/year) is calculated: conservative order-of-magnitude estimates are typically used for component failures and external causes, while human error frequency is usually estimated on the basis of operation complexity. The initiating event frequency of occurrence determines the value of Initiating Event Factor (F_{IE}).
In addition, the LOPA procedure includes the Enabling Factor (F_{EF}) calculation. The F_{EF} represents an environmental condition, whose occurrence contemporary to the initiating event leads to an accidental scenario featuring the characteristics and severity specified during the target factor evaluation phase (see Section 2.2). As an example, in the case of flammable release scenario, the enabling factor is related to the ignition probability (IP) that, in turn, depends on the amount of released substance and on its flammability characteristics.
The third factor taken into account in the risk compensation phase is the “exposure time factor” (F_{ET}), which aims to quantify the time portion of the overall duration of plant production when the dangerous operation is actually carried out and when the operators are actually present in the impacted area. Two parameters contribute to the determination of F_{ET}:

- Time at Risk (*TR*) defined as the percentage between the number of hours during which the considered operation is performed and the overall number of hours in which the plant is in operation, on a yearly basis. This parameter is applicable only to plant operating in batch mode.
- Probability of Exposure (*PE*), defined as the probability of operators presence in the proximity of the equipment involved in the accidental scenario.

The role of available means of accident prevention and mitigation is quantified by assigning a credit to each IPL that may intervene against the considered scenario. More specifically, the value of the credit factor F_{IPL} to be attributed is related to the IPL probability of failure on demand (*PFD*). The F_{IPL} represent a quantitative index to synthetically describe the effectiveness of safety measures design. Protection systems (fireproofing, water spray systems, pressure relief devices, etc.) are considered in the IPL assessment as well as procedural measures, company standards on good design practice and mechanical integrity. A key issue was to include personnel training to manage emergencies and the implementation of dedicated safety procedures in the assessment of IPLs. The complete list of credit factors is presented in Table 3 together with the correspondent definition.

As it can be seen from Table 3, F_{IE}, F_{EF} and F_{IPL} are calculated as a function of frequency or probability estimates ranging from 0 to 10^{-1}; *TR* and *PE* are used to correct the values of F_{ET}. Their contribution to the reduction of *TF* may become significant, corresponding to a credit F_{ET} at least equal to 1, only if their value fall below 10%.

Finally, the initial level of residual risk R_0 is calculated according to Eq(1), considering the contribution of both penalty and credit scores.

$$R_0 = TF - F_{IE} - F_{EF} - F_{ET} - \sum_{i=1}^{N} F_{IPL,i} \tag{1}$$

where N is the total number of IPLs already in place intervening to the mitigation and/or prevention of the scenario under analysis and $F_{IPL,i}$ is the credit factor associated to the *i*-th IPL.

If applying Eq(1) $R_0 \leq 0$, the residual risk is deemed acceptable and the implemented IPLs are considered adequate to guarantee operation within safety margins. On the contrary, if $R_0 > 0$ is obtained, actions should be taken in order to add as many IPLs as needed to reduce the residual risk at least to a value equal to zero. Hence, the final risk value R will be obtained as follows:

$$R = R_0 - \sum_{j=1}^{M} F_{IPL,j} \tag{2}$$

where M is the total number of IPLs needed to minimize the risk R and $F_{IPL,j}$ is the credit factor associated to the *j*-th IPL.

Table 3: Credit factors definition

Credit factor	Definition	Notes
F_{IE}	$F_{IE} = -\log_{10}(f)$	Related to the frequency of occurrence *f* (events/year) of the scenario initiating cause
F_{EF}	$F_{EF} = -\log_{10}(IP)$	Related to the ignition probability (*PI*) , which represents the enabling factor
F_{ET}	$F_{ET} = 2 \ for\ PE \leq 0.01$ $F_{ET} = 1 \ for\ 0.01 < PE \leq 0.1$ $F_{ET} = 1 \ for\ TR < 10\%$	Related to the probability of exposure (*PE*) and to the time duration of dangerous operation (*TR*) with respect to plant operations
F_{IPL}	$F_{IPL} = -\log_{10}(PFD)$	Related to protection system availability or probability of failure on demand (*PFD*)

3. Application to a case study

3.1 Definition of the case study

The methodology described herein was applied to the risk assessment of an existing plant located in an Italian industrial complex, part of a harbour area. The plant layout is shown in Figure 2a. In order to exemplify the methodology application, an extract of the results obtained in the analysis concerning the 1,3-butadiene storage section of the plant is reported in the following. The section houses a 250 m^3 storage tank operating at 2.25 barg and ambient temperature (the tank position is indicated by an arrow in Figure 2a). In the complete risk assessment, all the relevant scenarios for the loading and production phase were identified and investigated. However, for the sake of brevity, only the analysis regarding the scenario “release of 1,3-

butadiene (liquid phase) from a hole of 50 mm equivalent diameter into the catch basin, following the crane impact onto the tank shell" is detailed in the following.

3.2 Results and discussion

Figure 2b depicts the results of consequence analysis obtained using consequence analysis models (Van Der Bosh and Weterings, 1997). The most severe accidental scenario resulting from the release is represented by a flash-fire following the delayed ignition of butadiene vapors originating from the pool in the catch basin. According to Table 1, the lethality level for flash-fire is set to half of lower flammability limit concentration (1/2 LFL), as shown in Figure 2b. According to the physical effect map drawn by the software and considering the number of workers on shift in the impacted area during normal plant operation, more than 10 fatalities are foreseen. On the basis of the criteria outlined in Table 1, a TF value of 8 is thus attributed.

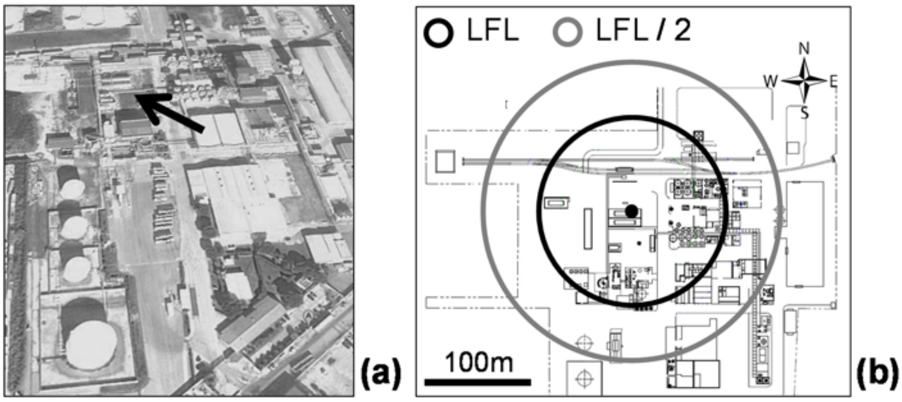

Figure 2: a) Plant layout; b) Consequence analysis of flash-fire scenario (LFL = lower flammability limit)

The data adopted and the assumptions made in the evaluation of credit factors to the estimation of initial risk level R_0 are summarized in Table 4.

Table 4: Assessment of the initial level of risk R_0 associated to the scenario in the case study

Factor	Value	Notes
TF	8	According to consequence analysis results and *TF* evaluation criteria given in Table 2.
F_{IE}	2	Crane impact frequency of occurrence equal to approximately 10^{-2} events/year.
F_{EF}	0	No credit. A mass of 20000 kg of butadiene is released within 15 minutes; hence there is a high ignition probability.
F_{ET}	1	Maintenance activities that require the use of a crane are carried out approximately once a year: TR<10%.
$F_{IPL,1}$	2	High design standards; good management and maintenance policy.
$F_{IPL,2}$	1	Procedure 1: direct operator supervision of maintenance activities.
$F_{IPL,3}$	1	Procedure 2: highly specialized and adequately trained personnel.
R_0	1	By applying Eq(1): initial level of residual risk R_0> 0 (not acceptable); additional IPLs are required

Table 5: Assessment of residual risk R after the implementation of a novel safety procedure

Factor	Value	Notes
$F_{IPL,4}$	1	Procedure 3 (to be implemented): maintenance activities that require the use of a crane must not be performed if the filling level of butadiene storage tank is higher than 10%; limit the number of operators on site during maintenance activities.
R	0	By applying Eq(2) and taking into account Procedure 3 residual risk R=0, hence safety requirements are met

The residual risk resulting from the analysis is positive. Therefore, additional measures are required to reduce the residual risk to an acceptable level; in the specific case, further IPLs may be implemented to remove the gap of 1 credit factor. The additional IPL consists in putting into action a new procedure concerning maintenance operations that requires the use of a crane: prescriptions are introduced to avoid the maintenance operations when the tank filling level is higher than 10 % and to reduce the number of workers involved in the maintenance activities. Therefore by applying Eq(2) and taking into account the new procedure adoption, the evaluated risk level becomes acceptable as summarized in Table 5.

The case study demonstrates that human actions based on specific procedures, or administrative controls which can directly implement the safety functions may have a key role in determining the risk associated to an installation (Paltrinieri et al., 2012). The present method, though simplified respect to conventional risk analysis methods, includes operational and organizational issues as key elements in the determination of risk.

4. Conclusions

In the present contribution, a methodology for the simplified risk assessment of chemical plants was outlined. The methodology takes advantage of the adoption of a LOPA approach to assess all factors influencing the frequency of occurrence of an accident scenario. Moreover, the consequence analysis was based on the use of sound physical models rather than expert judgment.

The results of methodology application to an existing plant were shown to exemplify the methodology. The case study demonstrated the effectiveness of the method in quickly detecting weaknesses in IPL design, enabling decision-makers to take prompt actions to keep plant residual risk under control.

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