Contribution to the evaluation of safety barriers performance

Hadef Hefaidh
LRPI Laboratory, University of Batna 2, Batna, Algeria and Applied Engineering Department, Institute of Technology, Kasdi Merbah University, Ouargla, Algeria
Mebarek Djebabra
LRPI Laboratory, Health and Safety Institute, University of Batna 2, Batna, Algeria, and
Sedrat Lila and Taghelabet Mouna
Health and Safety Institute, University of Batna 2, Batna, Algeria

Abstract

Purpose – The risk control is an unavoidable step in the risk management process. It is materialized by concrete actions of risks reduction in order to decrease their likelihood and/or their severity and also to preserve the environment. The paper aims to discuss this issue.

Design/methodology/approach – The main goal of the proposed methodology is to define the safety barriers (SB) that can be realized and their contribution to reduce major accidents scenarios that may occur in high-risk establishments.

Findings – In the proposed methodology, the authors present a combination of methods to prove the effectiveness of SB in an industrial installation.

Practical implications – The proposed methodology is a valuable help to industrialists to secure their industrial activities and preserve the environment at the same time.

Originality/value – The retained methods are often used separately for audit purposes or risk assessments of high-risk industrial facilities. In this paper, three methods have been selected and articulated in an approach for a better evaluation of risk control level.

Keywords LOPA, Safety, Evaluation, Barriers, Method, TRAM

Paper type Technical paper

1. Introduction

In major accidents prevention, the interest is often based on the potential hazards of facilities, which is analyzed through evaluating the harm effect distances of major accident scenarios (Chettouh *et al.*, 2018). In order to demonstrate that hazards have been identified and controlled, the influence of safety barriers (SB) on risk control should be taken into consideration (Sklet, 2006). This is discussed in this study.

The process of prevention and protection against the risk of major accidents consists of several fundamental steps. One of these steps relates to control measures assured by SB. They intervene either in prevention, minimizing the occurrence probability of hazardous events or in protection by reducing the consequences of accidents, occurrence of which could not be prevented (Ait-Ouffroukh *et al.*, 2018).

Evidently, several types of SB can be used in an industrial process (CCPS, 2001): equipment and process design, basic process control systems, alarms and human intervention, safety instrumented systems (SISs), post-discharge protection, contingency and response plans.

The above-mentioned SBs intervene sequentially to ensure the desired level of safety. Consequently, crossing a SB means its failure, which is represented by the probability of failure on demand (PFD).

World Journal of Science, Technology and Sustainable Development
Vol. 16 No. 1, 2019
pp. 56-68

2042-5945
DOI 10.1108/WJSTSD-08-2018-0055

In general, authors (Kang *et al.*, 2016; Hickey and Qi, 2013; Dianous and Fiévez, 2006) propose three main types of SB:

(1) technical safety barriers (TSB), which consist of a safety device or an SIS that prevents the sequence of events likely to cause an accident;

(2) organizational safety barriers (OSB), which consist of a human activity (operation) that opposes the sequence of events likely to cause an accident; and

(3) manual safety action systems (MSAS), which is a combination of the two previous types of barriers (TSB and OSB).

The interest in studying SB's performance lays at the origin of the published standards devoted to this subject. This is the case of AFNOR's PHARES standard for fire safety (NF S61-936, 2013), ISO 61508 (IEC61508, 2010) and ISO 61511 (IEC 61511, 2016) related to SIS and international SEVESO II directives (CEE 82-501, 1982).

Similarly, the study of SB's performance was at the origin of developing qualitative methods such as OMEGA 10 and 20 (INERIS, 2018), MADS-MOSAR (Smaiah *et al.*, 2017; Giraldo, 2007) and quantitative ones such as Layer of Protection Analysis (LOPA) (Willey, 2014).

Also note that the protection layer analysis carried out in the context of Control of Major Accidents Regulations (COMAH) (HSE, 1999) can be done by many methods such as (HSE, 1999): LOPA, Technical Risk Audit Method (TRAM), Dutch Major Hazard Assessment and Inspection Tool (AVRIM2), Protection Layer Analysis and Optimization (PLANOP) and Safety Barrier Diagrams (SBD).

The comparative study of these methods shows that LOPA is potentially used for the quantitative assessment of SB's performance while TRAM, AVRIM2 and PLANOP are often used as audit methods for industrial facilities where TRAM is considered as a quantitative method, whereas AVRIM2 and PLANOP are of the qualitative type. Finally, the SBD method is often used as a graphical representation of SB's allocation and its use is recommended in the circumstances where qualitative methods are applied (AVRIM2, PLANOP).

Ouffroukh *et al.* (2018), Singh *et al.* (2016) and Lunt *et al.* (2014) recommend the use of quantitative SB evaluation methods when possible and that qualitative methods are used only in the case of data unavailability. In this context, it is essential to emphasize the importance of the qualitative evaluation of SB that makes it possible to overcome the difficulties of acquiring quantitative data (Lowe and Taylor, 2013). However, this substitution of the quantitative assessment by the qualitative one must not be generalized. In our opinion, what needs to be generalized is the complementarity between qualitative and quantitative methods.

Within this context, the present paper is integrated with the aim of proposing an approach that articulates qualitative and quantitative methods of SB's performance evaluation. More specifically, the articulation of HAZOP, LOPA and TRAM and then their application on an LPG storage sphere called T002.

The purpose of the articulation of these three methods is to better evaluate the performance of SB.

2. The proposed methodology for the evaluation of the SB performance

The suggested methodology for the evaluation of the SB is provided by Figure 1.

In the proposed approach, step 1 is considered as the preparation for the SB performance evaluation that requires basic data and information. These data (PFDs, for example) can be retrieved from databases or documented sources. However, certain information related to the definition of initiating events, the consequences of accident scenarios and existing SB require the application of prior risk analysis methods where the HAZOP method is used (Saadi *et al.*, 2017; Pitt, 1994).

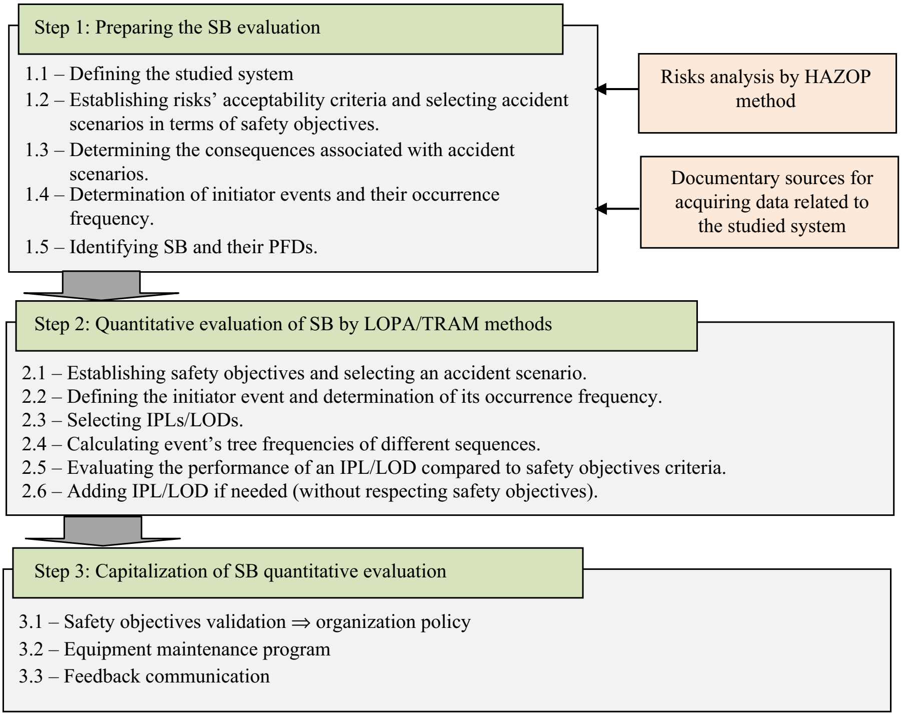

Figure 1.
The suggested methodology of SB's performance evaluation

Step 2 of the suggested approach is devoted to evaluating the performances of SB using the TRAM and LOPA methods, which share the same graphical representation by the event tree (see Figures 5 and 6). However, they differ into two levels:

(1) At the level of SB denomination and formulation:

- Concerning SB denomination, in LOPA, SB are considered as independent protection layers (IPLs). These IPLs are SB of prevention and/or protection, which are independent from each other and with the initiating event as well (Alejandro and Echeverria, 2016). However, in the TRAM method SB are called Lines of Defenses (LODs) that can be (Vectra, 2017): active, passive, physical or procedural.
- When it comes to IPLs/LODs formulation, an IPL is quantified in LOPA by a PFD while an LOD is quantified in TRAM by the following relation: $LOD = -\log_{10}(PFD)$.

(2) At the level of setting safety objectives (step 2.1 of Figure 1), the LOPA method uses the risk matrix (Figure 4) as a deduction tool for the safety objective. On the other hand, in the TRAM method, this safety objective ($\propto_N$) is integrated into an equation that makes it possible to evaluate the category of consequences of an event tree sequence (Equation (6)).

Giving these two differences between LOPA and TRAM, the objective of the proposed approach is to use these two methods in order to evaluate their relevance, especially for the definition of safety objectives (or risk acceptability), which is the main criterion for judging a SB performance.

The calculations required by the LOPA and TRAM methods for the evaluation of SB's performance are summarized below. Note that the explanation of these formulas is presented in their application on the example of sphere T002 detailed in Section 3.

Evaluation of SB's performances using the LOPA and TRAM methods

Calculations required by the LOPA method (Ouazraoui et al., 2013; CCPS, 2001). For each "*i*" sequence, leading to an accidental event (BLEVE, for example), its occurrence frequency (F_c) is obtained by multiplying the frequency of initiator event (f_i^I) and the average probabilities of failure on demand PFD_{ij} of each layer of protection:

$$F_C = f_i^I \times \prod_{j=1}^{J} \text{PFD}_{ij}. \tag{1}$$

The sequences are then grouped into consequence classes.

If a consequence class (BLEVE, for example) comes from a single sequence (sequence no. 4 in Figure 4), F_c is at the same time the occurrence frequency of this consequence class. On the other hand, if a consequence class (situation controlled in Figure 4, for example) groups together a set of sequences (sequences 1–3 in Figure 4, for example), the frequency of this consequence class is the sum of the frequencies of the "*k*" sequences corresponding to this consequence class.

If the accidental event is a fire, its occurrence is conditioned (in addition to the occurrence of the initiator event and failures of the IPLs) by an ignition. Hence, the occurrence frequency of the fire:

$$F_C = f_i^I \times \prod_{j=1}^{J} \text{PFD}_{ij} \times p^{\text{ignition}}. \tag{2}$$

In the case of a fire characterized by a human presence, the occurrence frequency of this accidental event must take into account this human presence. Hence, the new formulation of F_c:

$$F_C = f_i^I \times \prod_{j=1}^{J} \text{PFD}_{ij} \times p^{\text{ignition}} \times p^{\text{human presence}}. \tag{3}$$

If the occurrence of a fire in human presence causes injury, the occurrence frequency becomes:

$$F_C = f_i^I \times \prod_{j=1}^{J} \text{PFD}_{ij} \times p^{\text{ignition}} \times p^{\text{human presence}} \times p^{\text{injury}}. \tag{4}$$

If the accidental event is poisoning or burns caused by a hazardous chemical, its occurrence frequency is as follows:

$$F_C = f_i^I \times \prod_{j=1}^{J} \text{PFD}_{ij} \times p^{\text{presence humaine}} \times p^{\text{blessures}}. \tag{5}$$

Calculations required by the TRAM method (Roberts, 2000; Naylor et al., 2000).

- Consequences category (C_i):

$$C_i = -\log_{10}\left(\frac{\propto_N}{m}\right), \tag{6}$$

where $\propto_N$ is the acceptability criterion chosen for an accident, and "m" is the number of sequences leading to the same accident.
NB: comparing with the risk matrix (Figure 3), we consider four categories of C_i that are equivalent to s_i ($i = 1, \ldots, 4$).

- Frequency class (F_i):

$$F_i = -\log_{10}(f_i). \tag{7}$$

When f_i is the occurrence frequency of the initiator event.

- Risks evaluation (R_i):

$$R_i = f_i \times C_i \times P_i. \tag{8}$$

With:

$$P_i = \prod_j \mathrm{PFD}_{ij}. \tag{9}$$

NB: within Equation (9), the LODs are considered independent.

- Risks acceptability:

$$\mathrm{LOD}_{\mathrm{Required}} \geqslant C_i - F_i, \tag{10}$$

$$\mathrm{LOD}_{\mathrm{Available}\quad i} = -\log_{10}(\mathrm{PFD}_{ij}). \tag{11}$$

Step 3 of the proposed approach concerns the capitalization of results issued from the quantitative assessment of SB's performance (Figure 2). Two cases arise with the two methods selected (LOPA and TRAM):

(1) Capitalization of IPLs, where the F_c parameter of Equation (1) is compared with a tolerable frequency (F_t) retained for the same accidental event, if $F_c > F_t$ then the addition of another IPL becomes mandatory. Otherwise, the occurrence of the corresponding accidental event is considered as controllable.

(2) Capitalization of LODs, where the acceptability of the defense system is provided by the following relationship:

$$\mathrm{LOD}_{\mathrm{excess}} = \mathrm{LOD}_{\mathrm{available}} - \mathrm{LOD}_{\mathrm{required}}. \tag{12}$$

The result obtained from the application of this equation makes it possible to rule on the performance of the LODs. Indeed, if $\mathrm{LOD}_{\mathrm{excess}} > 1$ then the defense system is effective. Otherwise ($\mathrm{LOD}_{\mathrm{excess}} < 1$) the defense system requires strengthening the LODs.

In order to highlight the interest of the suggested approach for the evaluation of SB's performance, an application example will be presented in the following section.

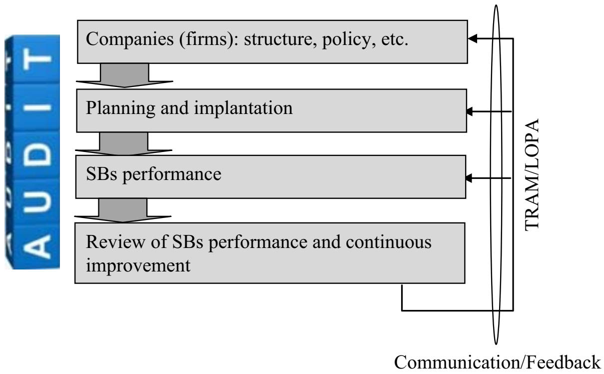

Figure 2. Contributions of quantitative evaluation of SB in an industrial organization

3. Applying the suggested approach to an application example

It is important to point that the choice of the LPG storage is justified, in addition to the reasons of the approach illustration, by the number of the occurred accidents for this type of petroleum storage products (Chettouh *et al.*, 2016), an analysis of several accidents related to petroleum products storage, highlighted three key facts (BARPI, 2012): the magnitude of the consequences associated with these accidents, common cause factors related to good organization and stakeholders training and finally the influence of natural events.

For these reasons, we are studying an LPG storage sphere system called T002 (Figure 3). In this, the operating characteristics are: the temperature is equal to 21°C, the operating pressure is equal to 5.34 bars, the calibration pressure of the safety relief valve is 5.98 bars, the sphere volume is 7,170 m^3 and the density is 535 kg/m^3.

Obviously, the studied system is equipped with SB that are designed to respect the following safety objectives:

$$\begin{cases} \text{Severity } s_2 \text{ must be at most frequency } f_3 \\ \text{Severity } s_3 \text{ must be at most frequency } f_3 \,. \\ \text{Severity } s_4 \text{ must be of frequency } f_1 \end{cases}$$

These objectives are deduced from the risk matrix in Figure 4.

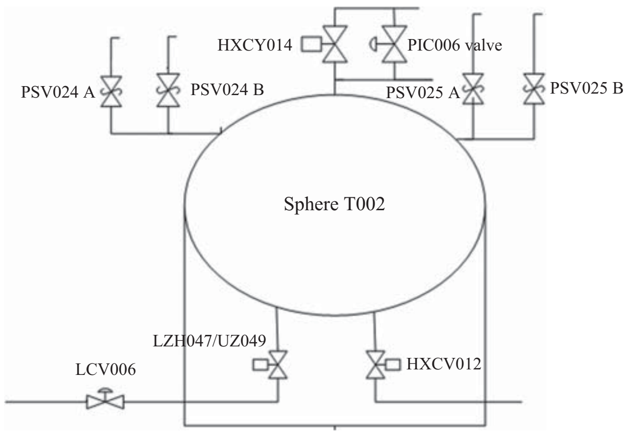

Figure 3. Main safety equipment/ instruments of the sphere T002

In the risk matrix (Figure 4), the four severity levels are catastrophic (impacts not only within the site but also off-site, irreversible environmental damage and large number of fatalities), critical (limited damage within the site, small number of deaths and/or injuries), minor (site disturbance, death and/or injury limited to a part of the site) and negligible (incidents without significant consequences). Similarly, the frequency levels are improbable (one occurrence per decade), probable (one occurrence every two years), frequent (one occurrence per year) and very frequent (one occurrence per month).

If we refer to the severity, the experience feedback shows that for this type of LPG sphere, an accident is qualified as major if it generates consequences with catastrophic severity (level s_4).

The identification of accident scenarios that can occur in sphere T002 is done by a risk analysis using the HAZOP method (Table I).

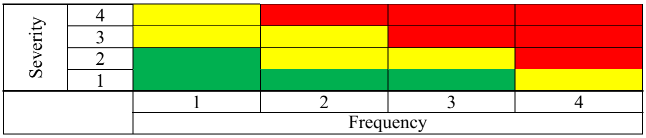

Figure 4.
Risks matrix used for evaluating SBs performance associated with sphere T002

Table I.
Extract from HAZOP analysis of TOO2 sphere (operating parameter is flow)

Keyword	Deviation	Cause	Consequence	Prevention	Protection
More than	High flow rate	Failure in the opening position of the LICV006	High level and high pressure in the sphere Ruin of spheres with leakage of LPG Fire in the zone with injuries of the operators	PICAH006 gives a high pressure alarm in the sphere LIAH048 shows in the control room a high level in the spheres LZH047 closes l'UZ049 HXCV014 depressurize the D006 and the sphere HXC012 to torch Compressor starting (K001) for decreasing the pressure PSV025 A and B to torch that protect spheres calibrated at 5.98 bar PSV024 A and B toward the atmosphere calibrated at 6.28 bars	ATEX zone Gas detection in the pumping and in the spheres zones Cooling crown on the spheres Flame detection on the pump near the flames that triggers the deluge water Retention zone with slope to burn pit Firefighting Internal Operation Plan (IOP)
		Failure in the closing position of the LICV006	High pressure in the sphere → Ruin of spheres and leakage of LPG Fire in the zone with injuries of the operators Explosion with fatalities	PICA006H shows in the control room Opening of the HXCV 014 in case of the high pressure alarm The manually by-pass of the PIC006 valve Design precision of spheres 5.98 bars PSV025 A and B to torch that protect spheres calibrated at 5.98 bar PSV024 A and B toward the atmosphere calibrated at 6.28 bars	

Note that in Table I, the deviations analyzed correspond to the operating parameter "flow." In this context, other operating parameters such as temperature, pressure and level can be selected and analyzed. For reasons of illustration of the exploitation possibilities of the HAZOP tables, we limit ourselves to the analysis of the operating parameter "flow" because the objective of this study is to highlight the complementarity between the three methods "HAZOP, LOPA and TRAM". Therefore, at this level of analysis of the T002 system by the HAZOP method, we aim to show the possibilities of using HAZOP tables with the other two methods (LOPA and TRAM).

From Table I, we retain two major accidents that are summarized in Table II.

We selected the two initial events (IEs) from the previous major accidents: failure of PIC006 and failure of LICV006 in opening position. According to the documented sources (ICSI, 2009), the occurrence frequency of these two IEs is 1.0E−1.

Evidently, the studied sphere T002 has SB that control the selected major accidents. These SB correspond to the IPLs/LODs (Table III) whose PFDsare provided by the reference (ICSI, 2009).

For recall, the safety relief valves PSV025 A/B and PSV024 A/B are arranged in parallel two by two. Thus, their PFDs are provided by the following equation:

$$\mathrm{PFD}_i = \prod_i (1 - \mathrm{PFD}_i). \tag{13}$$

Thus, we obtain the following PFDs for the safety relief valves:

$$\mathrm{PFDP}_{\mathrm{SV025A/B}} = \mathrm{PFDP}_{\mathrm{SV025A/B}} = 1.0\mathrm{E}{-04}.$$

The determination of $\mathrm{PFD}_{\mathrm{HXCV014}}$ is provided by:

$$\mathrm{PFD}_{\mathrm{HXCV014}} = \sqrt{a \times b} = \sqrt{1.0\mathrm{E}{-01} \times 5.0\mathrm{E}{-03}} = 2.24\mathrm{E}{-02}, \tag{14}$$

where a and b are the lower and upper bounds of the PFD values range (see Table III).

Recall that LZH047/UZ049 is an SIS with an integrated safety level (SIL) equal to 3. This SIL3 is supplied by the manufacturers of the site where the T002 system is located. Consequently, its PFD is equal to 1.0E−03.

Consequence	Severity	Description
BLEVE	s_4	The sphere may explode from the pressure. A leakage of LPG causes a fireball with a fatality with high numbers
Pool fire		Sphere rupture with a layer of liquid and possible gaseous cloud ignition with fire and fatality

Table II. The selected major accidents

IPLs/LODs	Mission	PFD
Alarm and operator	Report the occurrence of a dangerous event. Operator action to control this occurrence	1.0E−01
HXCV014	Depressurize both of the D006 and the sphere in case of high pressure	(1.0E−01 to 5.0E−03)
HXCV012	Release toward torch	2.2E−02
LZH047/UZ049	It is a safety instrumented system that stops the filling of the sphere when SIL is level 3	1.0E−03
PSV025A and B	Release toward torch	1.0E−04
PSV024 A and B	Release toward the atmosphere	

Table III. IPLs and LODs exist at the sphere T002

All of the IPLs/LODSs and their corresponding PFDs are identified. The two selected scenarios of accidents are then represented as event trees (Figures 5 and 6).

The obtained calculations from the event tree of Figure 5 with reference to the risk matrix of Figure 4 shows that the accident scenario is controlled by the IPLs (severity $= s_4$; $f^{\mathrm{BLEVE}}_{\mathrm{PIC006}} = 2.23\mathrm{E}-12$).

The obtained calculations from the event tree of Figure 6 with reference to the risk matrix of Figure 4 show that the accident scenario is also controlled by the existent IPLs (severity $= s_4$; $f^{\mathrm{Poolfire}}_{\mathrm{LCV006}} = 5.01\mathrm{E}-17$).

This approved effectiveness of IPLs by the LOPA method is also confirmed by the results obtained from the calculations according to the principle of the TRAM method (Table IV) where $\mathrm{LOD}_{\mathrm{excess}}$ for both accident scenarios is superior than unity.

According to the risk matrix (Figure 4), the two accident scenarios (BLEVE and Pool fire) are considered tolerable (frequency $= f_1$ and severity $= s_4$). Despite their tolerance by the risk matrix, two accident scenarios need a continuous monitoring (risks that are close to the unacceptable zone). This continuous monitoring consists of maintaining the IPLs/LODs efficiencies through an effective maintenance policy.

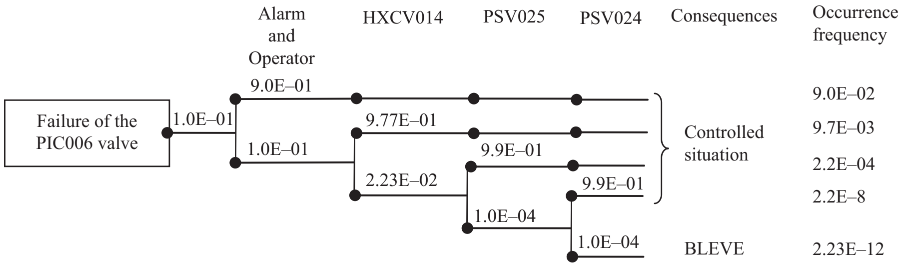

Figure 5.
Event tree of a "BLEVE" accident

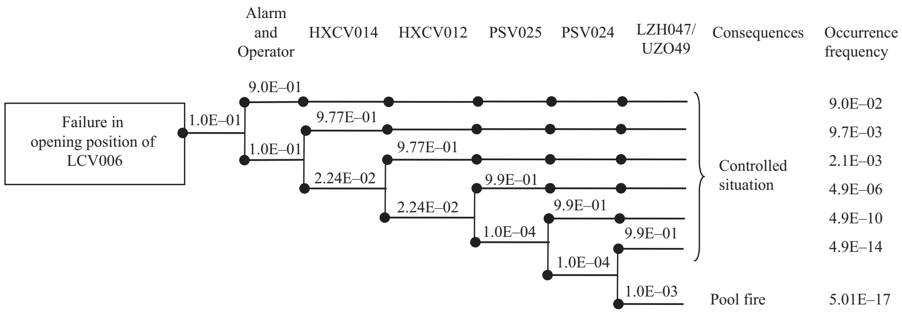

Figure 6.
Event tree of the "Pool fire" accident

Table IV.
LODs performance of the sphere T002

	"BLEVE" accident		"Pool fire" accident
C_i		6	
F_i		1	
R_i	6.0E−01		6.0E−01
$\mathrm{LOD}_{\mathrm{available}}$	10.70		15.3
$\mathrm{LOD}_{\mathrm{required}}$	5		
$\mathrm{LOD}_{\mathrm{excess}}$	5.7		10.3
Risk acceptability		Yes because $\mathrm{LOD}_{\mathrm{excess}} > 1$	

Another important observation is that the occurrence frequency of the accident scenario "Pool fire" is 1E−05, which is lower than the accident scenario "BLEVE." The results provided by the TRAM method have confirmed the previous observations where the LOD_{excess} of "Pool fire" scenario is equal to 1.5 times that of the "BLEVE."

This is due to the presence of two additional SB in the "Pool fire" scenario compared to the "BLEVE" scenario. As a result, the more we provide SB, the better control of the accident scenario is possible. In fact, an IPL/LOD crossing signifies its failure (represented by a PFD) which results in reducing the initiating event frequency by a reduction factor that is equal to the inverse of PFD of an IPL/LOD (Figure 7).

Moreover, it is important to note that in the TRAM method using the decimal logarithm in the calculations of the LODs leads to consider that an accident with a consequence (C_i) is ten times more severe than (C_{i-1}) consequence.

The TRAM and LOPA methods require an overview of risk's acceptability principles associated with accident scenarios. The overview shows that in the case where each accident scenario has only one initiating event (cases of "BLEVE" and "Pool fire"), the LOPA method provides an assessment of IPLs effectiveness as well as the one provided for LODs by TRAM. In fact, LOPA places the risk of these two accident scenarios in tolerable zone while TRAM provides an excess result that is not close to unity. These assessments provided by TRAM tend to consider that the risk of these two scenarios is "very acceptable" without a multi-criteria risk assessment (severity/frequency).

In other words, in case of accident scenarios that have only one initiating event, the advantage of SB's performance evaluation goes to the LOPA method. However, this advantage is for TRAM, in case of an accident scenario that has many initiating events that lead to the same consequence and where the LOPA method cannot be applied. Also, the interest of the TRAM method is not only to evaluate the category of consequence (C_i) for these types of accident scenarios (Equation (10)), but also to provide a more precise assessment of LOD's performance because LOD_{excess} results will be close to unity due to the fact that consequence category (C_i) will be lower ($m > 1$ in Equation (6)).

Another advantage of the TRAM method compared to the LOPA method is the possibility of considering LODs dependency, which is not the case in the LOPA method where IPLs must be totally independent from each other, in addition to the initiating event.

4. Conclusions

As a conclusion, both the TRAM and LOPA methods have many advantages and disadvantages when it comes to SB evaluation (IPLs/LODs). Therefore, the most important thing is the fact that the disadvantages of one method are the advantages of the other one.

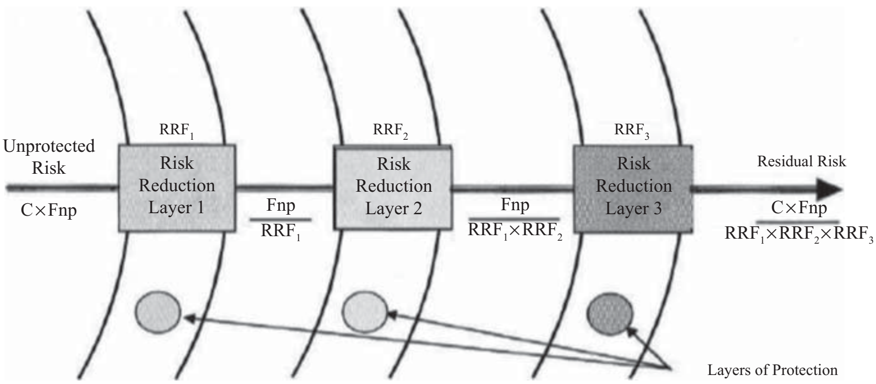

Figure 7.
Each layer of protection provides risk reduction

To illustrate our words, we quote the two restrictions of the use of LOPA, where we consider only one initiating event for a given consequence and the SB must be IPLs (independency criterion between SB must be fulfilled). These two restrictions of the LOPA method are overcome by TRAM that considers many initiating events and IPLs as lines of defense whose independency criterion is not important. Hence, the advantage of TRAM over LOPA.

Consequently, an effective SB's evaluation requires the mobilization of several methods.

As a perspective chosen for this study and considering the biggest disadvantage of the TRAM method, it is necessary to develop a formal logarithmic risk matrix in order to better assess accident scenarios risks according to the couple (consequences category, residual risk).

Glossary

SB	safety barriers
PFD	probability of failure on demand
TSB	technical safety barriers
SIS	safety instrumented system
OSB	organizational safety barriers
MSAS	manual safety action systems
COMAH	control of major accidents regulations
LOPA	layer of protection analysis
TRAM	technical risk audit method
AVRIM2	Dutch major hazard assessment and inspection tool
PLANOP	protection layer analysis and optimization
SBD	safety barrier diagrams
IPLs	independent protection layers
LODs	lines of defenses

References

Ait-Ouffroukh, L., Chaib, R., Ion, V. and Khchmane, L. (2018), "Analysis of risk and the strengthening of the safety technical barriers: application of Skikda (Algeria) oil refining complex", *World Journal of Engineering*, Vol. 15 No. 1, pp. 99-109.

Alejandro, C. and Echeverria, T. (2016), "On the use of LOPA and risk graphs for SIL determination", *Journal of Loss Prevention in the Process Industries*, Vol. 41 No. 1, pp. 333-343.

BARPI (2012), "Accidents ou incidents survenus sur des sites de stockage de GIL sous le régime de l'autorisation au titre de la rubrique no 1412: Période 01/01/1992 au 31/12/2012", Document du Ministère français en charge du développement durable/Direction Générale de la prévention des risques/Services des risques technologiques/BARPI, available at: www.aria.developpement-durable.gouv.fr/wp-content/uploads/2013/08/ED_CSPRT-sites-sto

CCPS (2001), *Layer of Protection Analysis*, American Institute of Chemical Engineers, New York, NY.

CEE 82-501 (1982), "risques d'accidents majeurs de certaines activités industrielles", INERIS-France, available at: aida.ineris.fr/consultation_document/1097

Chettouh, S., Hamzi, R. and Chebila, M. (2018), "Contribution of the lessons learned from oil refining accidents to the industrial risks assessment", *Management of Environmental Quality: An International Journal*, Vol. 29 No. 4, pp. 643-665.

Dianous, V.D. and Fiévez, C. (2006), "ARAMIS project: a more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance", *Journal of Hazardous Materials*, Vol. 130 No. 3, pp. 220-233.

Giraldo, F.-M. (2007), "Utilisation de l'ensemble méthodologique MADS/MOSAR pour l'évaluation des systèmes de barrières de sécurité", Thèse présentée à l'Institut National Polytechnique de Lorraine, Nancy.

HSE (1999), *A Guide to the Control of Major Accident Hazards Regulations 1999*, Vol. L111, Health and Safety Executive (HSE) Books, Londres.

Hickey, J. and Qi, V.E.H. (2013), "Effectiveness of accident models: system theoretic model vs the Swiss cheese model: a case study of a use coast guard aviation mishap", *International Journal of Risk Assessment & Management*, Vol. 17 No. 1, pp. 46-68.

ICSI (2009), "Initiating event frequency and availability of safety barriers", ICSI's Initiating Event Frequency Working Group, available at: www.icsi-eu.org/docsi/documents/24/csi0909-frequence-evenements.pdf

IEC 61511 (2016), "Sécurité fonctionnelle – systèmes instrumentés de sécurité pour le secteur de l'industrie process", International Electrotechnique Commission (IEC), Londres

IEC61508 (2010), *Functional Safety of Electrical/Electronic/Programmable Electronic Safety Related Systems*, International Electrotechnique Commission (IEC), Londres.

INERIS (2018), "Evaluation de la performance des barrières techniques de sécurité", Rapport d'étude No. DRA-17-165532-10199B, INERIS, Verneuil-en-Halatte, available at: www.INERIS.fr

Kang, J., Zhang, J. and Gao, J. (2016), "Analysis of the safety barrier function: accidents caused by the failure of safety barriers and quantitative evaluation of their performance", *Journal of Loss Prevention in the Process Industries*, Vol. 43 No. 9, pp. 361-371.

Lowe, J.-P. and Taylor, J.-Z. (2013), "Barriers to HACCP amongst UK farmers and growers: an in-depth qualitative study", *British Food Journal*, Vol. 15 No. 2, pp. 262-278.

Lunt, P., Ball, P. and Levers, A. (2014), "Barriers to industrial energy efficiency", *International Journal of Energy Sector Management*, Vol. 8 No. 3, pp. 380-394.

Naylor, P.J., Maddison, T. and Stansfield, R. (2000), "TRAM: technical risk auditmethodology for COMAH sites", *Hazards XV The Process, its Safety, and the Environment – Getting it Right*, IChemE Symposium Series, Vol. 147, Manchester, available at: www.icheme.org/communities/special-interest-groups/safetyandlossprevention/resources/hazardsarchive/hazardsxv.aspx (accessed October 10, 2018).

NF S61-936 (2013), "Système de sécurité incendie", ISBN: 978-2-12-166110-0, Paris, available at: www.academia.edu/37007901/Lines_of_Defence_Layers_of_Protection_Analysis_in_the_COMAH_Context (accessed October 10, 2018).

Ouazraoui, N., Nait-Said, R., Bourarache, M. and Sellami, I. (2013), "Layers of protection analysis in the framework of possibility theory", *Journal of Hazardous Materials*, Vol. 262 No. 11, pp. 168-178.

Pitt, M.-J. (1994), "Hazard and operability studies: a tool for management analysis", *Facilities*, Vol. 12 No. 13, pp. 5-8.

Roberts, I. (2000), "Application of TRAM Version 2.07 to the TOTAL LPG storage facility at Hauconcourt, France", AEA Technology Report No. AEAT/RSMS/RD00347/R1.

Saadi, S., Djebabra, M. and Boulagouas, W. (2017), "Contribution to the evaluation of the environment risks induced by the worn-water discharges of an Algerian tannery", *World Journal of Sciences, Technology and Sustainable Development*, Vol. 14 No. 4, pp. 268-278.

Singh, R.-K., Gupta, A., Kumar, A. and Khan, T.-A. (2016), "Ranking of barriers for effective maintenance by using TOPSIS approach", *Journal of Quality in Maintenance Engineering*, Vol. 22 No. 1, pp. 18-34.

Sklet, S. (2006), "Safety barriers: definition, classification, and performance", *Journal of Loss Prevention in the Process Industries*, Vol. 19 No. 5, pp. 494-506.

Smaiah, M., Djebabra, M. and Bahmed, L. (2017), "Contribution to the improvement of the MADS-MOSAR method for the modeling of domino effects", *Journal of Failure Analysis and Prevention*, Vol. 17 No. 1, pp. 440-449.

Vectra, A. (2017), "Lines of Defence/Layers of Protection Analysis in the COMAH Context", HSE Document, available at: www.hse.gov.uk/research/misc/vectra300-2017-r02.pdf (accessed October 5, 2018).

Willey, R.-J. (2014), "Layer of protection analysis", *Procedia Engineering*, Vol. 84 No. 1, pp. 12-22.

Further reading

Deloux, E. (2008), "Politiques de maintenance conditionnelle pour un système à dégradation continu soumis à un environnement stressant", Thèse de doctorat soutenue à l'Université de Nantes, Nantes, available at: https://tel.archives-ouvertes.fr/tel-00348191/document

Zandvoort, A. (2000), "Implementation of the Seveso – 2 guideline at a large chemical site in the Netherlands", *The Conference Forum Aldgate East*, *London*, *November 6-8*.

Corresponding author

Mebarek Djebabra can be contacted at: djebabra_mebarek@yahoo.fr