

RISK ANALYSIS, EVALUATION AND MANAGEMENT TOOL DEVELOPMENT FOR CIVIL EXPLOSIVES DEPOSITS

Burdea F.I., Moraru R.I., Burdea C.M.*

Abstract: This paper presents the results of in-depth research conducted over three years, in order to establish a methodological approach, as well as to develop specific application tools aimed to identify, formalize and structure the safety requirements applicable to risk management in storage facilities of explosive materials for civilian use in Romania, with the possibility of generalizing them to other similar deposits that are covered by the Seveso Directive on major accidents involving hazardous substances. With the use of analysis through the event tree at its core, this study centralizes, in addition to the methodology developed to manage the safety of explosives depots, also some of the results of its validation by applying the tools developed in seven explosives deposits in Romania. The results obtained are currently used in the development of a software package dedicated to the management operational and safety risks in civilian explosive storage facilities with at least national applicability, which will be the ultimate product of this research.

Keywords: risk management, civil use explosive, deposit, major accident, event tree, scenario, technical and organizational safety measure.

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Introduction

Major accidents involving hazardous substances pose a serious threat to humans and the environment, cause substantial economic losses and disrupt sustainable economic growth (Delvosalle et al, 2004; Besenyő and Sinkó, 2021; Becheikh, 2021). At the same time, the use of large quantities of hazardous substances is inevitable in some industrial sectors that are essential for a modern sustainably industrialized society (Moraru and Cioca, 2012; Plêta et al., 2020; Wo et al., 2021; Kriviņš et al., 2021). In order to minimize the associated risks, measures are needed to prevent major accidents and to ensure an adequate level of preparedness and response in the event of such accidents (Moraru et al, 2009; Grabara et al., 2019; Niciejewska and Kirliuk 2020; Oláh et al., 2019; Al Mazrouei et al., 2020; Wysokińska-Senkus and Górna, 2021).

The location of the industrial sites in the immediate vicinity of the areas likely to be affected by a possible accident has caused a significant increase in the level of technological risk (Ślusarczyk, 2018; Burdea and Moraru, 2020; Ulewicz et al. 2020;

* **Florin Ionel Burdea**, Ph.D. Candidate, **Roland Iosif Moraru**, Professor, Habil. Ph.D., **Crinela Monica Burdea**, Lecturer, Ph.D., University of Petroșani, Management and Industrial Engineering Department, Romania.

✉ corresponding author: roland_moraru@yahoo.com

✉ ionelburdea@yahoo.com; crina_bendea@yahoo.com

Kovács, 2017). The aim of the research summarized in this article, that of creating a methodology for quantitative analysis and explosion risk management in explosives storage facilities for civil use (Lentner et al., 2020; Polinkevych et al., 2021), is to create the premises for the implementation within the organization of measures necessary to prevent major accidents, and in the event of a major accident occurrence, to succeed, through the actions taken, to minimize its impact and amplitude.

Major accident prevention policy must be based on the principle of preventive action and the concept of sustainable development so that economically feasible technical safety measures prevent and limit the consequences of the use of hazardous substances on public health and the environment. Risk management must become a structured procedure for the qualitative and / or quantitative assessment of the level of risk posed by identified sources of hazard in explosives storage sites (ISO, 2018). The implementation of technical means of protection may increase costs, if these means are implemented after the completion of the design of a storage site or after its construction (Moraru, 2018).

The need and importance of developing a specific methodology for the analysis of the risk of explosion in deposits, lies in the following considerations:

- i. major accidents that can occur on an industrial site include explosions, fires and emissions of toxic substances. The consequences of such accidents can be serious, even catastrophic, materializing, in general, in human losses, the "ecological" damage to the natural environment and damage to property;
- ii. risk quantification involves identifying the potential for failure of the various components of the system, which can be achieved by constructing accident sequences in systems in which explosives are used or stored;
- iii. the analyzed system must be examined starting from the initiating events to determine which of these possible initiating events are also physically possible; for each of these initiating events, in order to increase the level of safety, additional safety and / or support measures must be identified that can be introduced in the system.
- iv. the methodology of analysis, assessment and management of major accident hazards (explosion) in the case of explosives deposits will facilitate the quantification of possible effects on neighborhoods and human health, including the delimitation of emergency planning areas

The aim of the research was to define a methodological approach, as well as specific application tools to identify, formalize and structure the applicable safety requirements for managing risks in explosive storage sites.

Literature Review

Research efforts in the field of explosion risk management, especially for strategic buildings and critical infrastructures, are not new, with numerous studies conducted in recent decades with the support of field experiments and / or numerical methods,

studies based on different approaches (Henrych, 1979; Bienz et al., 2004; Hamdan, 2016).

Numerous research studies have been carried out especially on the part of structural design and mechanical analysis (Ngo et al., 2007) of explosion-resistant structures and protection structures that could adequately withstand explosion waves (Buchan and Chen, 2007).

In general, mitigation measures that can be taken to protect against explosions can be classified as "non-structural" but also "structural". In the first case, "non-structural" mitigation measures can be either passive or active. An overview of explosion mitigation measures for coastal structures was provided by Cekerevac et al. (2017). The cited paper refers to different types of explosion-proof protective walls. According to the literature, various materials such as stainless steel, aluminum and fiber-reinforced polymers have been successfully tested for various explosive charges in the form of plates or sandwich panels (Cekerevac et al., 2017).

Another approach is represented by the so-called "Targets", which, in this context, represent the targets vulnerable to potential explosive events. Karlos et al. (2018) also include here the media effects (Benett, 2018). These may include critical infrastructure, key resources or key assets that are usually without adequate protection and that are open to the public through their purpose. However, explosion scenarios are well known to represent unexpected events that can lead to catastrophic consequences (Hayes, 1976; Liu, 2001). Consequently, the proper design of explosion protection of structures is strictly linked to adequate knowledge of explosion waves and related effects. On the structural side, the end result usually takes the form of a complex mathematical problem that must take into account the effects of high stress loading and dynamic nonlinearities. (Lee et al., 1978; Hamashima, 2003).

Figuli et al. (2020) presents a numerical model for the analysis of the explosion wave mode propagation. Based on research conducted in recent decades, various analytical solutions can be found in the literature (Figuli et al., 2016; Figuli et al., 2018). Many other influence parameters are then involved in the empirical description of an expected explosion wave, which is confirmed and can continue to interact with the affected soil or surfaces (Figuli et al., 2020).

By using the improved wording of the problem, the overpressure formula is determined using the scalar distance Z , based on a low weight W_R that takes into account several characteristics of the explosive charge and replaces the original term W . Typical values are $k_G - 0,5$ or 1 for detonations in a free space or on the ground surface, respectively (Kavicky et al., 2014).

A. H. Chowdhury and T. E. Wilt (2014), who present numerical analyzes to characterize the effects of explosions close to the ground surface and in contact with the ground surface on underground structures, focusing on improvised explosive devices manipulated, are in the same approach. The stages of the analysis include: i) identification of the characteristics and properties of the improvised explosive devices manipulated; ii) reviewing the dynamics of explosion propagation; iii)

identification of empirical equations for the propagation of explosion-induced shock waves; iv) performing a limited parametric study of the finite elements to determine the distribution of the pressure generated by the explosion; v) identification of empirical equations for the evaluation of the structural response; vi) identification of structural design standards or guidelines for underground structures subjected to explosive charges; vii) reviewing and identifying differences between the effects of explosive and seismic loading on an underground structure (Chowdhury and Wilt, 2014).

Detonation of explosive devices in the air, near the ground or on the ground and the transmission of explosion waves through the air and underground are evaluated to estimate the pressures generated. The most important parameter for determining the explosive wave characteristics of explosives is the total detonation heat, which is directly proportional to the total weight or mass of the explosive. Each explosive has a specific detonation heat per unit weight or mass. The maximum pressure that occurs at a location is defined as peak overpressure and is one of the values used to assess a structure's response to an explosive event. As the explosion wave reaches a given point, the overpressure increases rapidly from zero to the peak overpressure. (Baker, 1973).

The effects of the explosion include fire, rising temperatures, fragmentation due to washing and dust, and pose a danger to personnel and the environment. Attempting to quantify or predict ways of damage by analytical methods is extremely difficult. Bangash (2001) and McVay (1988) conducted theoretical and experimental studies on the deterioration of concrete structures subjected to the explosion of air from empty and coated explosive charges (Bangash, 2001; McVay, 1988). Empirical and experimental data were used to estimate whether local damage could occur. McVay (1988) found, however, that the results of small-scale test deterioration were difficult to scale to the actual states of deterioration observed in large-scale tests. Therefore, from the perspective of structural analysis, close explosions with localized loading are the most challenging to solve (McVay, 1988).

The equipment may be subjected to explosive pressures due to leakage into the structure through openings. If the opening is small enough, a "jet" may occur, leading to an increased explosion pressure and causing the equipment to fall or tip over (DOD, 2008). However, if the equipment is sufficiently attached to the structure, it is usually not affected by the increased pressure. Equipment damage can be classified as temporary or permanent failure. Permanent failure is either the actual destruction of the equipment or a failure that prevents the equipment from performing its intended function for an unacceptably long period of time (DOD, 2008).

The effects of air blast on humans are classified as primary, secondary, and tertiary (Richmond and White, 1966). The primary effects are caused by direct exposure to the explosion-induced pressure wave. Side effects are caused by debris generated by the explosion. Tertiary effects occur when the body is thrown by the explosive wave and is later projected into other objects (Richmond and White, 1966). The extent of

the injury depends on the weight and position of the person in relation to the explosive wave and the orientation of the person (i.e. standing, sitting) (DOD, 2008). Other effects are fire and inhalation of high dust concentrations (White, 1961). A critical factor is the duration of the explosion pressure increase (rapid increase with short duration, "fast filling" chambers versus slow growth with long duration "slow filling" chambers) (Richmond and White, 1966).

Hirsch (1966) stated that when comparing different types of trauma caused by the explosion, ear injuries are of secondary importance compared to the potential trauma that can occur in the lungs and other organs that produce air embolism in their vascular elements. The data presented in DOD (2008, Table 1-1) show that lung lesions can occur for short-term pressures (3 to 5 ms) between 207 and 552 kPa. It is also noted that temporary hearing loss may occur at pressure levels below 34 kPa, depending on the explosion wave that occurs in a normal direction to the eardrum (DOD, 2008; DOE, 1981). These facts indicate that the health aspect is not negligible in this problem (Gavurova and Kubak, 2021; Stefko et al., 2021).

Explosions are dynamic events that result in the generation of ground shock, which travels to the surface and underground. The severity of the ground shock depends largely on the amount of coupling between the explosive charge and the ground. Explosions in the air, with the exception of nuclear explosions, generate moderate to small amounts of ground shock due to limited coupling to the ground. Loads that are "tightly" buried (i.e., completely limited without surrounding voids) are the most severe, while loads surrounded by voids (for example, in a tunnel) generate less ground shock (Smith and Hetherington, 1994).

Another approach is the one used by Alfred Tan, Francis Loi, Andreas Bienz, who evaluate the system according to its components, namely: i) location; ii) infrastructure; iii) articles; iv) equipment; v) staff, vi) procedures / workflow (Tan et al., 2005):

Research Methodology

Over time, several types of initiating events have been identified as basis for detonation-explosion events of explosive substances, as well as safety measures whose application can prevent the occurrence of these events. The initiating events and the appropriate measures for prevention and protection against explosion-type phenomena can be grouped into several categories, as follows: i) Explosion due to shock waves; ii) Explosion due to mechanical energy; iii) Explosion due to thermal energy; iv) Explosion due to chemical energy; v) Explosion due to electromagnetic radiation (Hauptmanns, 1996); Papazoglou et al., 2009).

The Quantitative Risk Assessment (QRA) method has been widely used over the last 20 years as a framework for informed decision-making on risky industrial installations and sites, but is not frequently used for systems that concern activities involving the production, handling, transport and storage of explosive substances.

Figure 1 shows the steps followed during the research development in a structured manner in the form of a block diagram related to the research development logic.

The method of quantitative risk assessment (Pitblado et al, 1990; HSE, 2005) comprises three stages: 1. Analysis of event trees and their frequency of occurrence; 2. Assessing the consequences of event trees (explosions); 3. Integration of risk. This methodology was originally proposed and used to quantify risk in installations handling explosives (Papazoglou et al., 2005).

The first stage of the quantified risk assessment for explosives depots requires a complete analysis of all the possibilities of the initiating events that could lead to a potential explosion, materialized either by detonation or by explosion or the combination of these two types of explosive phenomena. Next, we analyze the safety measures that could be adopted, by installing technical safety barriers or by applying other measures of an organizational or other nature, to prevent any possibility of the initiating event already identified.

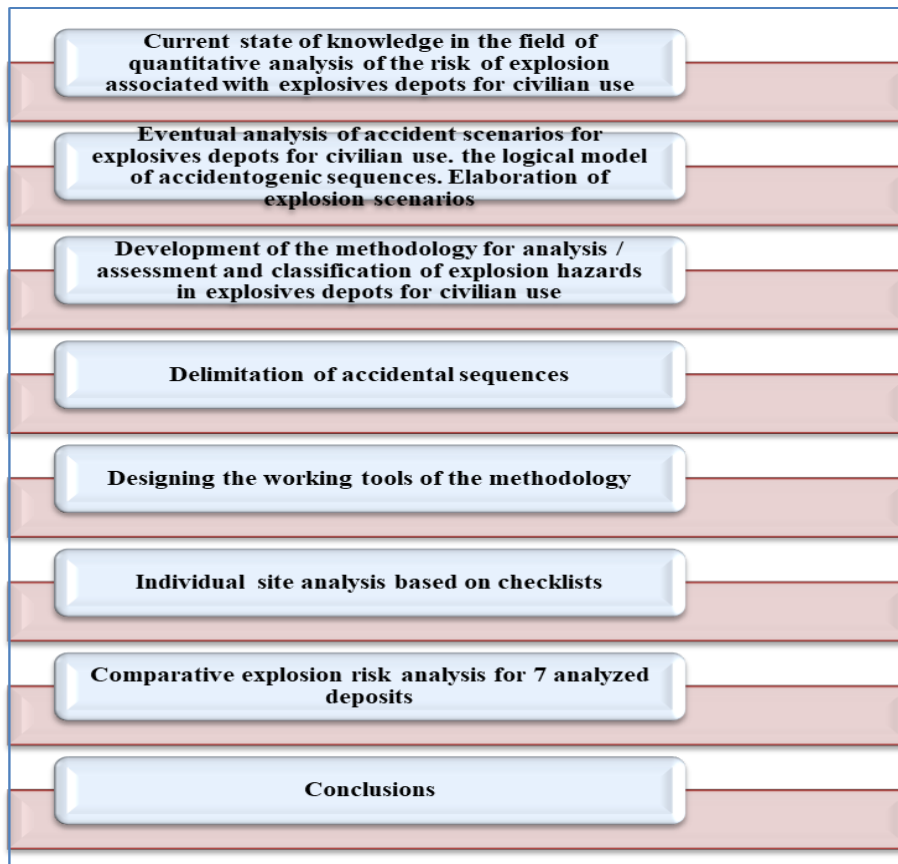


Figure 1: Research development logic

Source: Authors' elaboration

Accidental sequences are delimited, consisting of an initiating event, failures or specific successes of the functionality of the protection measures, including here the

human responses. Next, the accident sequences are grouped into classes (branches of the event tree) in which the sequences in a branch result in the same consequences. Finally, the frequency of each injury sequence (scenario) is calculated. The research approach we undertook involved: the elaboration of the main logical diagram, in order to highlight all the types of sources for initiating the events; inventory and systematization of applicable safety measures; graphic presentation of accident scenarios / sequences; analysis and evaluation of specific trees; synthesis of the obtained results and formulation of conclusions. The logical models used for the development of accident sequences are those of the event tree type.

A logical model of this type allows the quantitative analysis of risks but also the qualitative analysis of safety measures. Event tree analysis (ETA) involves determining the events that result from the failure of a component or part of the system. Starting from an initiating event or a fault of origin, the analysis through the event tree allows the estimation of the system deviation, taking into account in a systematic way the operation or failure of the detection, alarm, prevention, protection or intervention devices. The next step is to assess the probability of the explosion and quantify its possible consequences. At this stage, checklists are drawn up of the locations that will be analyzed, after which the level of explosion risk, the possible effects and the delimitation of the emergency planning areas are evaluated, a basic element in the risk management process.

For the classification of major-accident hazards, both the probability of an accident and its effects must be taken into account. The level of risk can be defined as the product between the probability of an event occurring and its effects.

The risk matrix, developed based on the principle of the methodology of the Layer of Protection Analysis - LOPA, (Gowland, R., 2006) for the classification of explosion hazards is presented in Table 1.

Table 1. Risk matrix for identifying major accident hazards

Severity / Frequency	Insignificant G1	Low G2	Mean G3	High G4	Very high G5	Catastrophic G6
F6	6	12	18	24	30	36
F5	5	10	15	20	25	30
F4	4	8	12	16	20	24
F3	3	6	9	12	15	18
F2	2	4	6	8	10	12
F1	1	2	3	4	5	6

The interpretation of the level of consequences of a major accident on human health and of the effects produced in the neighborhood, on the environment or constructions, is presented in Table 2.

Table 2. Severity of a major accident on human health and the effects produced in the neighborhood

Severity	Very low G1	Low G2	Mean G3	High G4	Very high G5	Catastr ophic G6
Human	No effects	Minor injuries	Hospitali- zation	Hospitali- zation, disability	Disabilitie s, death	Several deaths
Environ ment	No effects	Slight damage, quick fix	Significa nt damage, possible repair	Major damage, difficult repair	Severe damage, difficult or impossible repair	Severe damage, disasters

The probability classes to be considered are presented in Table 3:

Table 3. Likelihood of the event

Class	Qualitative probability	The value of probability
F1	Nearly impossible	$P < 10^{-6}$ / year
F2	Rare	$P = 10^{-5} - 10^{-6}$ / year
F3	Improbable	$P = 10^{-5} - 10^{-4}$ / year
F4	Possible	$P = 10^{-4} - 10^{-3}$ / year
F5	Probable	$P = 10^{-3} - 10^{-2}$ / year
F6	Highly probable	$P = 10^{-2} - 10^{-1}$ / year

Through the proposed methodology, the deposits are analyzed in comparison to a so-called "complete" site, where all possible components are installed and all safety measures have been adopted, provided by the event tree and the sequence of accidents for the analyzed trigger factor.

After identifying the site, it is compared with the safety measures characteristic of a complete site, where all the necessary safety measures are implemented, followed by the effective analysis of the analyzed deposit, by identifying possible triggers and existing safety measures. After their identification, the risks were analyzed for the individual scenarios, until the moment when it is verified if the analyzed deposit reaches the risk level of the complete deposit, otherwise it is necessary to introduce new safety measures. .

In the next stage, the consequences of the event are analyzed, based on the risk scenarios, being calculated the possible effects of the explosion, followed by the delimitation of the emergency planning areas. All these represent absolutely necessary basic tools in the management of the explosion risk, depending on the delimitation of these areas being drawn up the emergency intervention plans, the applied measures, the areas that are possible to be evacuated, etc.

Results and discussion

The direct causes (initiating events) that can generate explosion-type events on the sites where operations with explosives are carried out, identified based on the literature as well as following the analysis of events produced in Romania, were organized in the form of a Master Logic Diagram (Figure 2).

The events located at the base of the tree represent direct causes of the occurrence of the explosion / ignition type event and can be materialized in installations or processes in specific forms, being considered as initiating events of explosions (triggering risk factors).

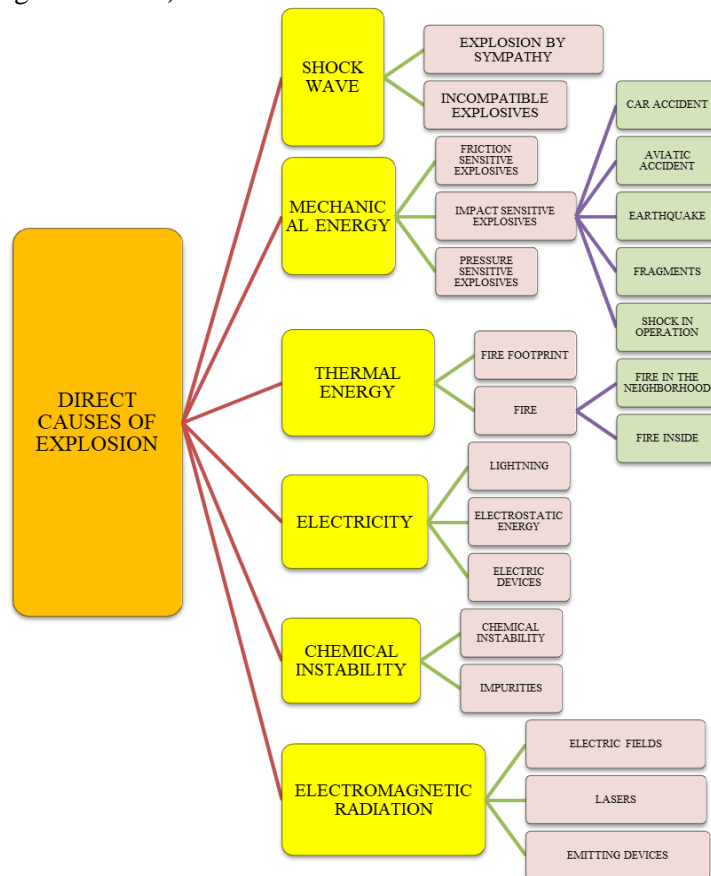


Figure 2: Master Logic Diagram chart: direct causes of explosion (triggers)

Source: Authors' elaboration

The initial events that may evolve into a direct cause of an explosion are synthesized in Table 4.

Table 4. Initial sources of risk (Triggers-D) for explosives deposits

Symbol	Description
D1	Incompatible explosives
D2	Car accident inside the warehouse
D3	Plane crash
D4	Earthquake
D5	Explosions in the neighborhood
D6	Impact sensitive explosives
D7	Friction sensitive explosives
D8	Atmospheric surges, lightning
D9	Sparks from malfunction of electrical equipment
D10	Sparks due to static electricity
D11	Chemically unstable explosives
D12	Impurities in the composition of explosives
D13	Electro-explosive devices
D14	Outdoor fires
D15	Indoor fires

The **technical safety measures** adopted for each of the initial sources of risk are highlighted in Table 5.

Table 5. Technical safety measures (T) for explosives deposits

Symbol	Technical measure description
T1	Constructive protection of the warehouse (building) - type of warehouse
T2	Arrangement of separate rooms for storage of incompatible explosives
T3	Protective barriers between storage rooms
T4	Shock-resistant equipment
T5	Racks and shelves arranged so that the impact energy is less than the ignition energy
T6	Storage of explosives on shelves racks in packing boxes so as to avoid friction and / or frictional energy
T7	Lightning protection
T8	Earthing of electrical equipment and protection of personnel
T9	Explosive distribution flow adapted to reduce storage time
T10	Prevention of contact with impurities - Maintenance and cleaning of storage spaces
T11	Explosion-proof encapsulation of electrical equipment
T12	Disposal of sources
T13	Dispersion currents with energy lower than ignition energy

T14	Elimination of laser radiation sources
T15	Elimination of radio sources
T16	Elimination of mobile telephone radiation sources
T17	Outdoor and indoor fire detectors
T18	Trained operators for fire detection and operational intervention
T19	Water tanks, wells water or connection of the storage to the water network, fire hydrants
T20	Equipped with high pressure pumps, diesel or electric pumps
T21	Equipped with sprinklers, sprinklers
T22	ADR authorized vehicles, fire protected
T23	Fire extinguishers
T24	Barricades, fences, earth waves for protection of the deposit

Some of the safety measures presented in Table 5 apply to the prevention of multiple sources of risk. Proper construction of warehouses (T1), concrete protective barriers (T3) and fencing of warehouses with protective barricades, earth waves (T24) are applied to prevent explosions in case of car accident (D2), shocks caused by earthquakes (D4).) and to prevent the spread of any other explosions produced in the vicinity (D5), to stop / decrease the propagation of the effects of the explosion outside the warehouse, implicitly in its vicinity. Fire prevention and control measures (T17-T23) have a common applicability both in the case of outdoor fires, for example vegetation fires in the vicinity of depots (D14), and fires inside depots (D15). Another type of measures, especially of an organizational nature, can *complement* the technical measures and are systematized in Table 6.

Table 6. Organizational safety measures (O) for explosives deposits

Symbol	Organizational measure description
O1	Procedures for avoiding joint storage of incompatible explosives
O2	Procedures for labeling explosives by compatibility groups
O3	Procedures for licensing and licensing of vehicles and drivers for the transport of dangerous goods (ADR)
O4	Procedures for limiting the speed of vehicles transporting explosives inside the site
O5	Procedures for clearing of vegetation inside the warehouse
O6	Procedures for operating / maintenance procedures to avoid shocks caused by impact
O7	Procedures for handling, loading / unloading and transport to avoid shocks caused by impact
O8	Selecting equipment to reduce impact, shock absorption
O9	Procedures for handling, transport and storage for prevention and reduction of contact and friction between stored explosives
O10	Verification of equipment according to ATEX procedures
O11	Procedures for performing explosives stability tests
O12	Adapting explosives storage flow to shorten storage times
O13	Quality control

O14	Production control
O15	Procedures for space maintenance and cleaning
O16	Procedures and checks for measuring electromagnetic fields
O17	Procedures for preventing laser radiation

These organizational measures complement the technical measures, creating links that influence the probability of occurrence of the event. For example, the measure on the adoption of procedures for the joint storage of incompatible explosives (O1) and the measure on the labeling of explosives by compatibility groups (O2) lead to a more rigorous application of the technical measure for the storage of incompatible explosives in separate rooms (T2), thus implicitly reducing the likelihood of an explosion-like event caused by incompatible explosives (D1).

In this stage, the accident sequences and the event trees were elaborated for each of the 15 triggers, for each of these scenarios being identified the safety barriers that can be applied. The graphical presentation of the event tree for the trigger factor type D1 - Incompatible explosives is given in Figure 3, and the accident sequences are presented in Table 7.

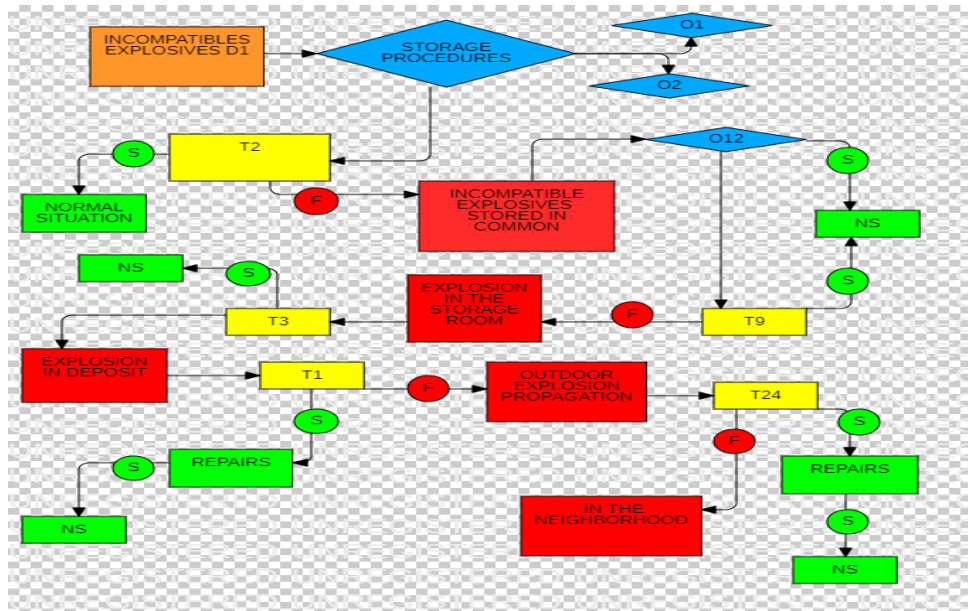


Figure 3: Event Tree for D1 trigger – Incompatible explosives
Source: Authors' elaboration

Table 7. Accident sequences for trigger factor D1 - Incompatible explosives

D1*O2e*O1e*O12e*T2e*T9e*T3e*T1e*T24e
D1 D1*O2e*O1e* O12e *T2e*T9e*T3e*T1e*T24r
D1*O2e*O1e* O12e *T2e*T9e*T3e*T1r*T24r

D1*O2e*O1e* O12e *T2e*T9e*T3e*T1r
D1*O2e*O1e* O12e **T2e*T9e*T3r*T1r*T24r
D1*O2e*O1e *O12e **T2e*T9e*T3r*T1r
D1*O2e*O1e* O12e *T2e*T9e*T3r
D1*O2e*O1e* O12e *T2e*T9r
D1*O2e*O1e* O12e *T2r*T9r
D1*O2e*O1e*T2r
D1*O2r*O1r*T2r

where *r*-success; *e*-failure

Thus, we can exemplify, according to Figure 3 and Table 7, the tree of events and accident sequences corresponding to the trigger factor type D1 - Joint storage of incompatible explosives, where prevention measures are represented by the development and implementation of procedures O2 and O1, which involve the labeling of explosives by compatibility groups and the avoidance of storage of incompatible explosives in the same room. After these initial organizational measures, technical prevention measures of type T2 are provided. If these measures are not sufficient, they are followed by a complex of technical and organizational measures T9 and O12 which involve the creation of a flow of use and distribution of explosives which ensures the shortening of storage times.

According to the above, checklists have been developed to identify the technical and / or organizational safety measures applied to each of the analyzed deposit. (Table 8),

Table 8. Checklist of triggers / safety measures according to the event tree and the sequence of events - Matrix of the results of the conformity assessment

Check - checklist of triggers / safety measures according to the tree and the sequence of events-Matrix of the results of the conformity assessment																
Factor code	Trigger	Measure code	Deposit A		Deposit B		Deposit C		Deposit D		Deposit E		Deposit F		Deposit G	
			a	u	a	u	a	u	a	u	a	u	a	u	a	u
D....																

In the next stage, checklists were developed and completed for the identification of explosive materials stored on the analyzed sites, according to the model presented in Table 9.

Table 9. Inventory table of stored explosives

Table of inventory of hazardous substances stored in the analysis site									
No	Dangerous substance name	CAS No.	Characteristics	Quantity	Total storage capacity	Physical condition	Storage mode	Storage / operating conditions	Location in the depot

Based on the checklists, a number of 7 storage sites for explosives were verified in Romania. For security and information protection reasons, in the present paper these storage sites are referred to only literally A-G, without making any reference to the location of the site or other information that by publication could constitute a source of risk for the security of these explosive materials storage sites.

Next, for example, we present the comparative analysis for the trigger factor D1 - Incompatible explosives, according to Figure 4 which shows the comparative summary analysis table and Figure 5 which shows the event tree and the comparative diagram of the risk level variation for the 7 analyzed deposits. From the data centralized in this table the following can be seen:

- i. The initial risk level for all sites was set at a maximum of 36 (6 on the frequency scale and 6 on the consequence scale).;
- ii. For the complete site, as the safety measures provided by the event tree are introduced, the value of the risk level decreases to the minimum value of 1, located in the area of negligible risk.;
- iii. For most of the analyzed sites, the lack of procedures type O12 - Procedures for adapting the explosive storage flow to shorten storage times and T9 - Explosive distribution flow adapted to decrease the storage time corresponding to the adaptation of the storage flow was found so as to storage times are reduced. However, given the specificity of each deposit, the lack of these measures and procedures, given that all other measures are implemented, does not lead to major risks, the level of risk reaching the value of 4.
- iv. In order to reduce the risk level, according to the established conclusions and the fact that the calculated risk level has the value 4, located in the field of negligible risk, it is necessary, but not mandatory, to implement procedures for adapting the explosive storage flow to reduce storage time and for one of the sites, the construction of concrete protection barriers between the storage rooms as a measure to limit the effects.

Trigger factor symbol	Event tree	Measures identified	Full Deposit			Deposit A			Deposit B			Deposit C			Deposit D			Deposit E			Deposit F			Deposit G			
			Risk matrix			Risk matrix			Risk matrix			Risk matrix			Risk matrix			Risk matrix			Risk matrix			Risk matrix			
			Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	Yes	No	Risk level	
D1 - Incompatible explosives	Initial condition	Explosion			6			6			6			6			6			6			6			6	
			O1	X	5	6	3	X	5	6	3	X	5	6	3	X	5	6	3	X	5	6	3	X	5	6	3
			O2	X	4	6	4	X	4	6	4	X	4	6	4	X	4	6	4	X	4	6	4	X	4	6	4
			T2	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1
			O12	X	2	5	1	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1
			T9	X	2	4	8	X	3	5	1	X	3	5	1	X	3	5	1	X	3	5	1	X	2	4	8
			T3	X	2	3	6	X	3	4	1	X	3	4	1	X	3	4	1	X	3	4	1	X	2	4	8
			T1	X	2	2	4	X	3	3	9	X	3	3	9	X	3	3	9	X	3	3	9	X	2	3	6
			T4	X	1	1	1	X	2	2	4	X	2	2	4	X	2	2	4	X	2	2	4	X	2	2	4

Figure 4: Trigger factor D1- comparison table of results

Source: Authors' elaboration

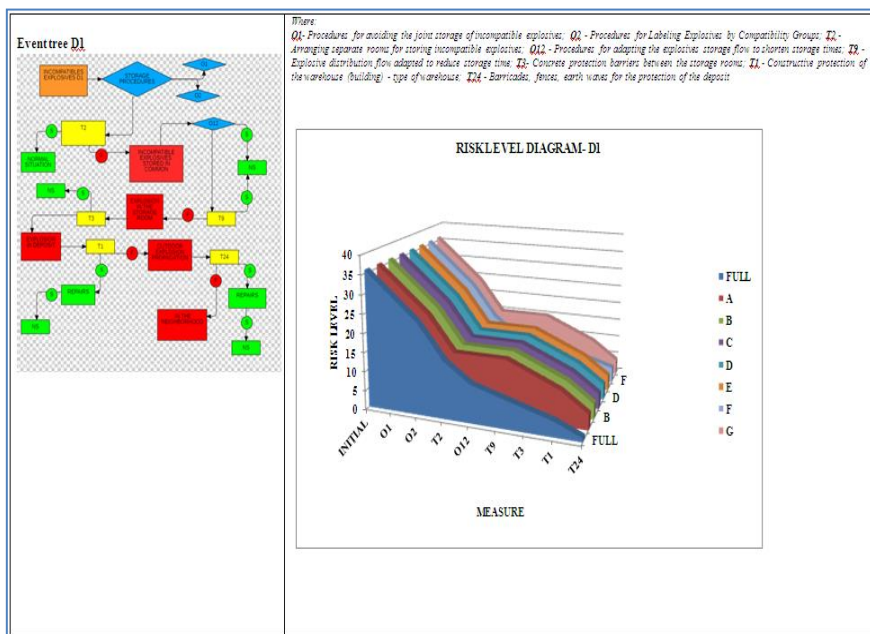


Figure 5: Event tree and comparative risk diagram for the trigger factor D1

Source: Authors' elaboration

Conclusion

Previous studies emphasized that risk management based on quantitative risk assessment has been widely used over the last 20 years as a framework for informed decision-making on risky industrial sites, but is not frequently used for systems that concern activities involving the storage of explosive substances (Pitblado et al, 1990; HSE, 2005). Having as starting point the approach proposed by Papazoglou et al (2005) and ISO 31.000 standard (ISO, 2018), the methodology developed in this research for explosion risk management in the case of explosives deposits, allows the quantification of possible effects on neighborhoods and human health, including the delimitation of emergency planning areas.

It should be stated that based on the research presented, the RESICEX software was developed, for risk management in explosives depots for civilian use. This approach can be used to assess the possibility of an explosion at the storage site, by identifying all possible triggering risk factors and associated safety measures. Accident sequences for a hypothetical "*complete*" location involve the generation of event trees for each possible trigger of the event; in this situation, the typical frequencies and the probability of occurrence of failures are assigned subjectively, expressing the analyst's appreciation for the relative probability of occurrence of the event, attributing to each of the safety barriers a reduction in the frequency of explosion. The study does not refer to the possible risks generated intentionally by the human factor (deliberately malicious actions), such as terrorist actions on storage sites.

The validation of the approach based on the elaboration of accident sequences and event trees was achieved by its practical application at a number of 7 storage sites, relevant in the field of explosives storage, each of them being authorized locations according to the legal provisions in force and under SEVESO directives.

Extrapolating the results in order to generalize the application of the methodology to other industrial organizations requires support and interest both from the representations of these organizations but also from the institutions with control and verification attributions in the field.

Risk management within any unit must be subordinated to the objectives that form an integrated, coherent and convergent system to the general objectives. This approach allows the organization to define and implement a risk management strategy that starts from the top and is integrated into the routine activities and operations of the organization. The ubiquity of uncertainty regarding the knowledge and reliability of the data used, the measures to be taken to limit the consequences or minimize the probability of occurrence, the degree of subjectivism of the assessments make it quite difficult to accurately formalize the procedures applied.

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ANALIZA, OCENA RYZYKA I ROZWÓJ NARZĘDZI DO ZARZĄDZANIA ZŁOŻAMI CYWILNYCH MATERIAŁÓW WYBUCHOWYCH

Streszczenie: W artykule przedstawiono wyniki pogłębionych badań prowadzonych na przestrzeni trzech lat, mających na celu ustalenie podejścia metodologicznego, a także opracowanie konkretnych narzędzi aplikacyjnych mających na celu identyfikację, sformalizowanie i uporządkowanie wymagań bezpieczeństwa w zakresie zarządzania ryzykiem w obiektach magazynowych materiałów wybuchowych do użytku cywilnego w Rumunii, z możliwością uogólnienia ich na inne podobne depozyty, które są objęte dyrektywą Seveso w sprawie poważnych awarii z udziałem substancji niebezpiecznych. Wykorzystując analizę poprzez drzewo zdarzeń w swoim rdzeniu, badanie to centralizuje, oprócz metodologii opracowanej w celu zarządzania bezpieczeństwem składów materiałów wybuchowych, również niektóre wyniki jej walidacji poprzez zastosowanie narzędzi opracowanych w siedmiu złożach materiałów wybuchowych w Rumunii. Uzyskane wyniki są obecnie wykorzystywane do opracowania pakietu oprogramowania dedykowanego do zarządzania ryzykiem operacyjnym i bezpieczeństwa w cywilnych magazynach materiałów wybuchowych, o zastosowaniu co najmniej krajowym, który będzie ostatecznym produktem tych badań.

Słowa kluczowe: zarządzanie ryzykiem, materiał wybuchowy do użytku cywilnego, depozyt, poważna awaria, drzewo zdarzeń, scenariusz, techniczny i organizacyjny środek bezpieczeństwa.

民用爆炸物存放处的风险分析、评估和管理工具开发

摘要：本文介绍了三年来进行深入研究的结果，以建立一种方法论方法，并开发旨在识别、形式化和结构化适用于存储设施风险管理的安全要求的特定应用工具。罗马尼亚民用爆炸材料，并有可能将它们推广到塞维索指令涵盖的关于危险物质重大事故的其他类似沉积物。本研究以事件树为核心进行分析，除了为管理炸药库安全而开发的方法外，还集中了通过应用在罗马尼亚七个炸药矿床开发的工具进行验证的一些结果。所获得的结果目前用于开发至少具有全国适用性的民用爆炸品储存设施的管理操作和安全风险的软件包，这将是本研究的最终产品。

关键词：风险管理，民用爆炸物，存款，重大事故，事件树，情景，技术和组织安全措施