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DOCTORAL FIELD: INDUSTRIAL ENGINEERING

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THESIS

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CONTRIBUTIONS TO INCREASE THE OPERATIONAL SECURITY OF TECHNICAL INFRASTRUCTURES FOR THE STORAGE OF DANGEROUS SUBSTANCES OF THE TYPE OF EXPLOSIVES FOR CIVIL USE

CONTRIBUTIONS TOWARDS OPERATIONAL SAFETY INCREASE OF TECHNICAL INFRASTRUCTURES INTENDED FOR STORAGE OF DANGEROUS SUBSTANCES LIKE CIVIL EXPLOSIVES

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CONTENT

1. The context, motivation and finality of the thesis

This doctoral thesis is the "finished product" of an extensive approach to study/ analysis/synthesis theoretical and experimental research, designed and carried out based on the author's practical experience, a vast documentary study carried out from the specialized literature applicable to the field, studies systematic and coherent of a theoretical/applicative nature carried out in the last 5 years.*industrial and occupational security*" and for the specific elements of legislative compliance which constitute the foundation on which any risk minimization approach is founded, regardless of their nature.

The thesis addresses a current topic in the field of the development of the risk assessment infrastructure associated with unwanted events such as major accidents resulting in explosions of explosive materials, which can occur at the level of warehouses and other categories of industrial or civil facilities production/storage of explosives, in order to prevent and reduce the loss of human lives and material goods, as well as the damage caused to environmental factors.

Actuality and importance of the research derives from the fact that the development of process industries involving the processing and storage of dangerous substances has determined the increase in the cases of technological and chemical incidents and accidents in particular and not only, revealing the need for a particularly careful and serious control of chemical processes , in order to prevent events with particularly serious consequences. The explosives industry, which involves the manufacture and/or storage of explosives, fireworks and other pyrotechnic articles, are important sources of major accident risk. While the number of deaths and other injuries resulting from a major accident is routinely collected, equivalent data are not consistently collected for other types of impacts, including environmental damage and clean-up costs.

Explosives and pyrotechnics (E&P) sites represent approximately 6% of the more than 12,000 Seveso sites in European Union and European Economic Area (EU/EEA) countries. Accidents involving explosives still occur regularly. Since 2000, almost every year t there have been two to four major accidents recorded in the EU's eMARS data base. In the last five years alone, there have been twenty major accidents in Europe involving explosives.

The theoretical and practical substantiation of the explosion risk assessment methodology at civil explosives warehouses, presupposed the following research steps:

- the analysis of specialized literature dealing with the issue of major risk specific to explosives warehouses;
- the study of security measures aimed at reducing the risks of major accidents generated by the specific dangers of explosives warehouses with an emphasis on the factors responsible for their implementation;
- highlighting the analysis and assessment of the vulnerability and safety of explosives warehouses;
- the integration of malicious acts in the process of assessing the risks of major accidents;
- establishing the methods of presenting the results of the evaluation of the explosion risk specific to explosives warehouses.

The motivation of the doctoral thesis is related, on the one hand, to the necessity and possibility of developing/adapting the methodological mechanisms for evaluating the explosion risk specific to industrial sites in the field of civil explosives, and on the other hand to ensure the theoretical and practical premises regarding the configuration of methodological tools good practice in the field of security/explosion safety when hazardous substances such as explosives are involved, to allow unitary orientation and guidance in the proper management of the most plausible accident scenarios that can occur at the level of an economic operator.

The main objectives other theses consist in the conceptualization of the quantitative evaluation mechanism of the explosion risk produced following the detonation of explosive materials and the development of methodological tools for evaluating the effects generated by explosions, based on the results of research undertaken in the field of integrated security of technical infrastructures intended for the storage of dangerous substances such as explosives for use civil. These main objectives are achieved by achieving *derived/specific objectives* namely: the configuration of the theoretical-applicative way of expressing the main accident scenarios according to the layout of the explosive structures and exposure at the level of an industrial site, the development of the simplified mechanism of fatality in the case of the detonation of explosive materials, a case study on the assessment of the risk of explosion at a pilot economic operator with activity in the field of civil explosives, carrying out computer simulations of the explosion effects produced following the detonation of explosive materials.

The derived/specific objectives, in turn, are achieved by achieving the following p*rimary objectives*: the study of the specialized literature by consulting the main bibliographic references in the field of interest of the thesis, the definition and conceptualization of the explosion risk generated by explosive materials, the establishment of the criteria for the acceptability of the explosion risk, the definition and disposition of the explosive and exposure structures at the level of an industrial site, description of the main explosion effects produced by the detonation of explosive materials.

Research strategy which was the basis for the realization of the work concerned three big *directions of action* in technical-scientific terms, respectively:

- The beginning of the thesis with the study of specialized works in the field of explosion risk assessment when dangerous substances of an explosive nature are involved, in order to strengthen the theoretical basis on which the assessment of the security of industrial sites in the field of civil explosives is founded. Thus, following the interrogation of multiple data bases with scientific articles, we considered for the realization of this work a number of 168 established bibliographic references;
- The second dimension of the research consisted in the conception and realization of the analytical mechanisms for substantiating the technical-scientific instruments for evaluating the explosion risk generated following thedetonation of explosive materials;
- The last dimension of the research consisted in the computerized evaluation of the explosion risk, using a proven, state-of-the-art software, as well as in the realization of experimental research of the explosion effects.

However, the research undertaken in the field of interest of the thesis also presents certain limitations, in view of the fact that most of the data and information specific to the technological processes of manufacturing and storing explosive materials are confidential, and the costs related to specialized tests and trials are high, having considering the prices of these explosive products, as well as the equipment and software used, the tests being only repeatable and very rarely reproducible (since the products are destroyed after the tests).

2. The objectives of the doctoral thesis

Overall Objective (OG)of the doctoral thesis was defined from the very beginning as the identification, development and application concretization of some analytical, graphic, experimental and numerical simulation means applicable in the practice of companies/industrial organizations or other organizational entities whose object of activity is transport, the storage, manufacture and/or use of explosive materials, with the stated aim of contributing to increase the range of strategies and measures available to minimize the risk of explosion associated with this category of dangerous substances in industrial security management, general business management and increasing resilience by strengthening the response capacity in emergency situations, from an anticipatory perspective.

We aimed, as concrete and punctual results, the development and integration of formalized methods/tools, including in the form of specialized software, usable by experts who carry out their activity in the area of the conception/design and use of explosives manufacturing/storage sites, in a way particularly, but simultaneously also of users of dangerous substances that fall into the category of explosives for civil and industrial use.

In order to achieve this basic objective, he considered that it is necessary to follow andsuccessively achieve the following *specific derived objectives:*

OS 1. Analysis and synthesis of the evolving regulatory framework related to the research field, *by carrying out a documented study regarding the temporal, principled and evolutionary development of the normative/legislative framework that regulates the control of the dangers of major accidents (the Seveso directives), with a special focus on statistical data related to unwanted events in this category generated by explosive materials.*

OS 2. Realization of a realistic and current landscape regarding the development of decision support systems in the management of major risks associated with explosives, *through the categorical and systematic approach to risk management requirements, the identification of hazards and the security report, the particularities of quantitative explosive risk analyses, the analysis / assessment of major accident risks in terms of input data, result categories and applicable tools. Within this specific objective was also included the investigation of the possibilities of applying the systemic methods and dynamic analysis of the Seveso type sites, as well as the support systems for adopting the decision regarding the risk of major accidents and the realization of a synthesis regarding the management and evaluation software of major risks available worldwide.*

OS 3. Conceptualization of the explosion risk generated by explosive materials and its quantitative evaluation *and the development of the methodology for quantitative evaluation of explosion risk, which is based on the specialized use of the concept of risk specific to industrial sites intended for operations with explosive materials.*

OS 4. Development of methodological tools for evaluating the effects generated by explosions;

OS 5. Development of a case study regarding the evaluation of the explosion risk at an economic operator pilot with activity in the field of civil explosives, with application to two Seveso-type installations: *Facility 1 – Basic storage for civil explosives; Installation 2 – Production of AUSTINITE type civil explosive by mechanical mixing of ammonium nitrate and diesel fuel.*

OS 6. Computer simulations of the explosion effects produced following the detonation of explosive materials: *the analysis, assessment and classification of major accident (explosion) hazards in the case of explosives deposits, the quantification of the possible effects on the neighborhoods and on human healthand the establishment of emergency planning areas.*

OS 7. Open field experiments for air pressure wave on mobile platform with TESTES pressure sensor,*in view of the study on the propagation of the pressure wave during the detonation of explosive charges.*

2. Logical scheme of the stages followed in the development of doctoral research.

In fig. 1.1. the succession of the stages completed in accordance with the development logic of the research materialized in the thesis is represented synthetically, in strict accordance with the specific objectives previously defined and subsumed to its general objective. Although it does not constitute an operational scheme, the graphic representation highlights to a large extent the coherence of the conducted studies, taking into account the partial results obtained following the completion of each of the phases, gradually.

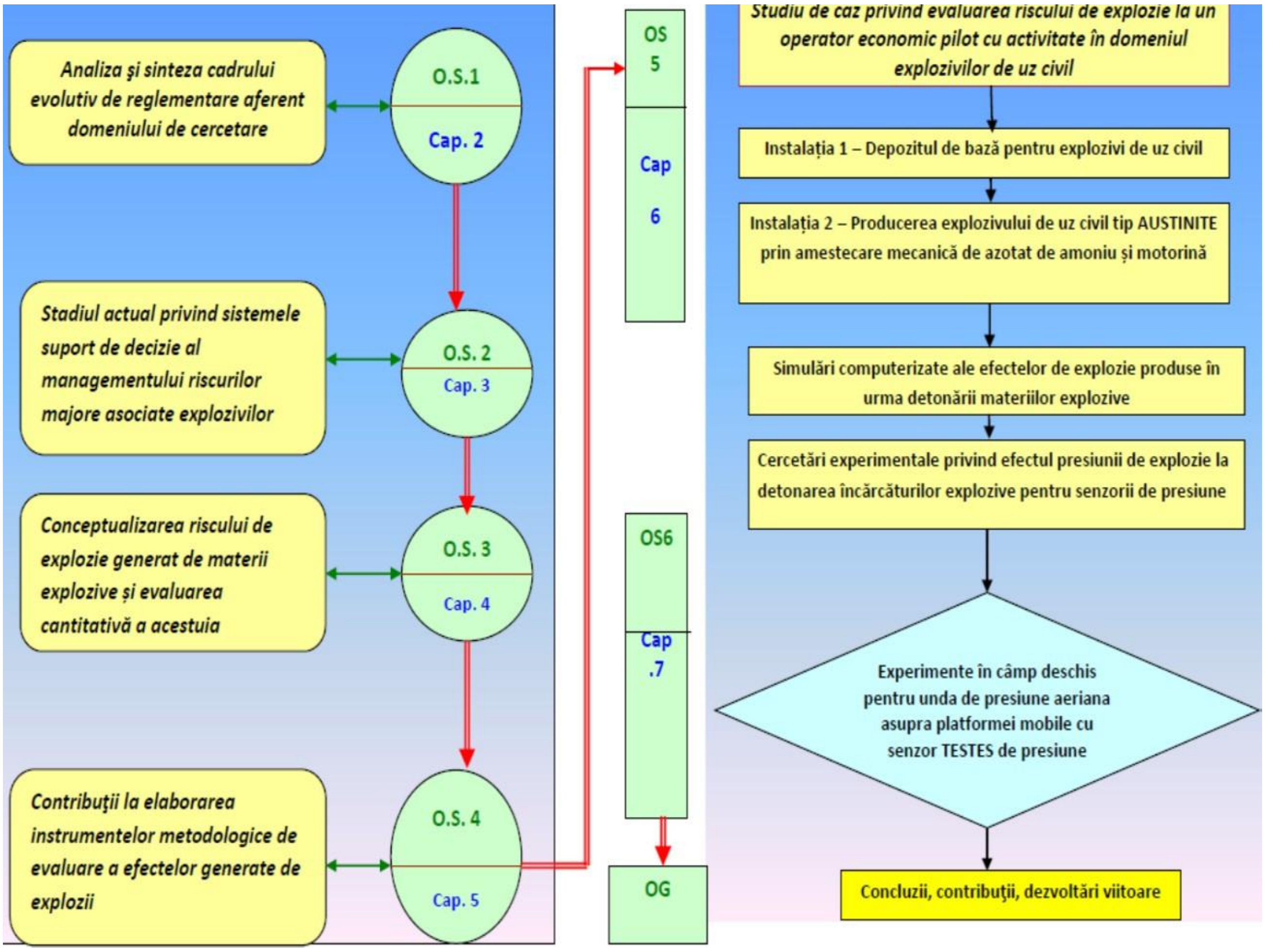

Fig. 1.1. Logical flow chart of the phases of the doctoral research, correlated with the specific objectives derived from the general objective of the study

3. Synthesis regarding the structure and content of the thesis

From a structural point of view, the thesis contains the lists of figures (in number of 103 graphic representations, screenshots and images), tables (in number of 59) and acronyms used, an introductory chapter with a specific theme and 6 content chapters, in which a last chapter of final conclusions and personal contributions is added, totaling a number of 234 pages, of which 10 pages represent the actual thesis and 10 pages represent the "Bibliography" which has a number of 168 bibliographic references. The list of scientific papers published/disseminated by the author during the doctoral internship is included as an Appendix.

Since the explosives used in the industry must be correlated with the nature of the environments in which they will detonate, considering the type of effects generated within this process, knowing the parameters that characterize the explosives is essential, whether we refer to the safety ones for carrying out work under maximum conditions security, whether we refer to thermodynamic, physicochemical or ballistic parameters to achieve the proposed objective.

Into the **first chapter**, called "***Introduction: the importance and necessity of the theme. Objectives and structure of the thesis"*** the general considerations, the main and specific objectives, the motivation of the thesis and a brief summary of the paper are presented. The logical flow diagram of the phases/stages of the study facilitates the easy visualization and understanding of the concept and the evolutionary structure of the undertaken scientific approach, in congruence with the fixed objectives. The importance, actuality and necessity of the theme are explained synthetically so as to justify and argue the theoretical, practical and methodological - application purpose of the intended results.

Chapter 2, titled ***"Analysis of the evolving regulatory framework of major industrial accidents"***, presents a synthetic exposition of the main regulations applicable at international, European and national level in the field of major accident risk assessment specific to industrial sites intended for specific operations with explosive materials.

Currently, measures are regulated at the national level to prevent major accidents involving dangerous substances, as well as to limit their consequences on human health and the environment, to ensure a high level of protection throughout the national territory, in a consistent manner and effective, given that our country ranks 10th among European countries in terms of the number of objectives that fall under the scope of the Seveso Directive.

Starting from the SEVESO paradigm, explained from the beginning and as a legislative and regulatory evolution, we have synthetically illustrated the temporal evolution of the European Union legislation dedicated to major industrial accidents and - very relevant - the status of the implementation of the Seveso III Directive on the European level. From the perspective of this analysis, successful implementation has meant that EU Member States have effectively adopted national measures and that the number and severity of accidents is decreasing. Reporting on Member States' implementation of Directive 96/82/EC over the past 7 years has indicated that implementation continues to improve with each reporting period. The number of "sites" was increasing, but the number of major accidents remained stable. For that period, an average of 27 major accidents were reported each year. Of particular note was the significant drop in the number of deaths and injuries. Another point to mention is that the Office for Major Accident Risks (MAHB) of the Joint Research Center of the European Commission provides political, scientific and technical support to Member States in the implementation of Seveso III. MAHB also provides an industrial accident risk analysis reference center for benchmarkingmodels and tools and for site-specific risk assessment applications and general policy implementation, as well as accident data management and analysis systems.

Particular aspects of E&P sites were detailed in parallel with the specific regulationsin the field of civil explosives, highlighting the fact that the rapid progression of explosive accidents is critical when considering emergency response. Although E&P hazards are broadly similar, they cover different scales of both risk and consequence. This diversity is reflected in the different nature of the spectrum of major accident risks associated with explosives.

The results of the analysis carried out in this chapter allowed - further - to detail the research with reference to the risk analysis/assessment tools associated with the industrial sites for the storage/production of explosive materials.

Major accidents highlight the fact that ensuring security in systems with complex technologies was not just a matter of getting people to follow simple rules of prevention and protection. Competent and well-intentioned operators may not control risks in transient, unclear or unexpected circumstances. Starting from this reality and from the specific objective no. 2 default, **chapter 3**, which bears the title "***The current state of decision support systems for the management of major risks associated with explosives"*** aimed to rapidly summarize the transition of the analytical paradigm of risks from "classic" professional risks and "high-risk" high- tech dangers to global risks, by reviewing the FRAM Model of Functional Resonance, the principle scheme of defense in series (Reason's "Swiss Cheese" model), the TRIPOD Basic Model and the Bow Tie Method as the main tool for representing accident scenarios. Major risk management was analyzed from the perspective of evolving requirements, how to identify hazards in line with the security report, with special emphasis on the particularities of the quantitative analyzes of explosive risk. The existing tools worldwide, and found in the specialized literature,intended for the analysis / assessment of major accident risks were systematized multi-criteria, taking into account the input data, the categories of results in close connection with applicable tools. The final section of this chapter describes synthetically the application of the systemic method in risk analysis, with reference to "*The MADS methodology for analyzing system malfunctions*", the MOSAR method derived from its already established spirit and applicability and the DyPASI. Methodology for dynamic risk analysis for Seveso sites. In a natural way, the decision-making support systems regarding the risk of major accidents are "inventorized", a synthesis of the most widely used (worldwide) major risk management and assessment software packages is elaborated (MSIAC QD; RBESS; WRA; SAFER ; UN Safer Guard Quantity Distance Mapvi; *IMESAFR*).

Into the **chapter 4** called "***Conceptualization of the explosion risk generated by explosive materials and its quantitative assessment"*** a series of theoretical contributions are presented on the explosion risk generated during the detonation of explosive materials, both from the perspective of the conceptualization of the notion of its definition, with an emphasis on the way of quantitative assessment considering the acceptability criteria and the accident scenarios configured based on the disposition of explosive structures and exposure at the level of the industrial site, as well as regarding the conceptual substantiation from a grapho-analytical point of view of the simplified fatality mechanism caused by the explosion, when hazardous substances of an explosive nature are involved. It is highlighted that in the field of risk analyzes associated with explosion-type events caused by specific operations with explosive materials, to estimate the result indicator, the logarithmic scale is usually used, because: i) the range of values specific to the area of interest for carrying out the risk estimation can include several orders of magnitude; ii) lends itself very well to quantitative risk assessment; iii) compliance with the principle of proportional logic is ensured, according to which multiplying the risk with a constant value leads to a constant separation (variation) of it. The main mechanisms of damage through death or injuries (major or minor), as well as through material destruction, following the occurrence of an explosion-type event during specific operations with explosive materials are also highlighted. A set of four risk criteria was developed for the management of the explosion risk specific to operations with explosive materials and the main scenarios for the disposition of explosive structures(PES) and exposure (ES) at the level of industrial sites intended for specific operations with materials were established explosives. The risk analysis must be carried out in a manner that recognizes the mechanism of compliance with the mathematical legitimacy of "*additive*" of risk values taking into account its nature. In this sense, the risk-based disposition of explosive structures (PES) and exposure structures (ES) within an industrial site intended for carrying out specific operations with explosive materials, is done by ensuring that all PES-type structures that expose a structure of type ES to a " *individual risk*" significantly are taken into account in the analysis and by evaluating "*group risk*". So, "*thegroup*" for a PES is considered to consist of all persons exposed to a significant risk from that PES, and "*group risk*" is the total risk for all individuals in the group. "*Group risk*" shall be determined by summing all "*individual risks*". Within the process of quantitative evaluation of the explosion risk generated following the detonation of explosive materials, the estimation of the manifestation of the dangers identified through the associated risk factors, will be carried out on the basis of scientific calculation algorithms and established grapho-analytical models, considering databases substantiated from the results of experimental research regarding the characterization of the effects and consequences related to typical event scenarios with different exposures at predefined distances, in accordance with standard safety criteria, using the technique of extrapolation of the effects of the far field to the area in the vicinity of the epicenter of the explosion (near field), of course preserving the size of the proportion of the modeled effect.The approach to the simplified mechanism of fatality caused by an explosion-type event following the detonation of explosive materials (MSFEXP) is based on a traditional way of using the extrapolation technique of field effects, the general concept of the elaborated model being highlighted grapho-analytically at the end of this chapter.

Aspects relating to ***"Contributions regarding the development of methodological tools for evaluating the effects generated by explosions",*** are highlighted in **chapter 5**, which presents at a synthetic level the methodological and grapho-analytical tools for evaluation and modeling of the main explosion effects produced following the detonation of explosive materials, clearly marking the technical and scientific results related to: the calculation of the mitigation effects against the explosion generated by overpressure and impulse; assessment of the degree of damage to the human component / structural collapse of a building affected by the explosion; evaluation of the thermal hazard factor generated during the detonation of explosive materials; modeling the dispersion of material fragments generated by explosions. Potential fatality mechanisms are analyzed in parallel and can be grouped into four branches of sequential steps: Pressure and Impulse (the explosion produces a blast wave described by both overpressure and impulse); The structural response (two consequences are evaluated here: the collapse of the building and the breaking of the windows – the design of the material fragments); Debris (the debris branch combines the dangerous fragments resulting from the detonation of explosive materials depending on the kinetic energy); Thermal (the thermal branch is used only for Hazard Division (HD) 1.3 explosives that produce mass fires). The generalized grapho-analytical tool for evaluating the human component damage mechanism as well as the structural collapse of a building affected by an explosion is based on the use of the simplified mechanism of fatality caused by an explosion-type event following the detonation of explosives (MSFEXP), presented in chapter 4. The modeling of the design effect of debris that can affect the human component and/or the resistance structure of installations and buildings located on a site intended for specific operations with explosive materials is based on the quantification of the impact characterized by the throwing speed and the mass of material fragments resulting in following the detonation of explosive substances, taking into account the type of material (steel or concrete) and the loading conditions of the resulting debris. For the most truthful modeling of the design effect of material fragments resulting from the detonation of explosive materials, the new resulting model is used, with non-zero azimuthal variation, according to which the amplitude along the central direction varies according to the class interval of the fragments, and the standarddeviation is a constant angle.

In the **chapter 6** entitled "***Case study on explosion risk assessment at a pilot economic operator active in the field of civil explosives***",a section is presented dedicated tothe evaluation of the explosion risk specific to the preparation and storage activities of the ANFO type explosive, at the level of the industrial site within an economic operator active in the field of civil explosives. Numerical applications are developed for two installations, namely:
1. Base storage for civilian explosives and *2. Production of AUSTINITE-type civilian explosive by mechanical mixing of ammonium nitrate and diesel fuel.*

The framing of the locations, the analysis of the explosion risk is carried out, using the methodology "*based on consequences*", which is based on the assessment of the consequences of possible accidents, without to explicitly quantify the probability of occurrence of these accidents.

In this way, we avoided quantifying the frequencies of occurrence of potential accidents and the associated uncertainties. The basic concept was the existence of one or more very serious scenarios, which are defined according to past experiences, historical data, expert judgment and qualitative information obtained from hazard identification. Scenarios with major or catastrophic consequences were taken into account. In order to identify the worst possible accident scenario at the level of the studied industrial site, reference scenarios (hypotheses) were defined and established, highlighting for each individual case the significant aspects of configuration (scenario coding, event type, possible location, causes/effects, production conditions, the value of overpressure, effects on constructions and on human health, the affected area, the result of computer modeling, etc.), respectively: (A) The accident scenario regarding the explosion of a quantity of 50 kg of ETNT at Warehouse III – staples; (B) The accident scenario regarding the explosion of a quantity of 300 kg of ETNT at Warehouse III – staples; (C) The accident scenario regarding the mass explosion of a quantity of 1300 kg of ETNT at Warehouse III – staples; (D) Accident scenario regarding the mass explosion of a quantity of 3000 kg of ETNT at Warehouse III – AUSTINITE; (E) Accident scenario regarding the mass explosion of a quantity of 20,000 kg of ETNT at Warehouse I – LAMBREX, EMILEX, NITRAMON, AUSTINITE; (F) Accident scenario regarding the mass explosion of a quantity of 12500 kg of ETNT at Warehouse I – AUSTROGEL; (G) The accident scenario regarding the explosion of a quantity of 20000 kg ETNT of stored ammonium nitrate due to the spread of a fire at the Ammonium Nitrate Warehouse. In order to prevent emergency situations that may occurat the level of the industrial site that was the object of the case study, at the end of the chapter, general prevention and protection measures of a technical-organizational nature were provided.

Chapter 7,***"Computer simulations of the explosion effects produced by the detonation of explosives",***highlights the results of the computer simulations of the explosion risk specific to industrial sites in the field of civil explosives, that where obtained with specialized software in the field of explosion risk assessment (IMESAFR), in order to determinate the risk parameters(drawing overpressure curves, of risk curves and contour maps regarding the design of fragments resulting from detonation with highlighting the affected areas: lethal area/ area of major injuries/ area of minor injuries)as well as a series of experimental research on the determination of the effect of explosion pressure on detonation explosive carges using, for monitoring state-of-the-art equipment(sensors of overpressure, high speed camera). For computerized explosion risk assessment specific to industrial sites in the field of civil explosives i used the software specialized in the field of explosion risk assessment type IMESAFR v2 Bundle at the warehouses of explosive for civilian use , which ensures the necessary premises for development in objective and high conditions software for explosive storage facility personnel that calculates safe distances to explosive storage facilities and can determine the safety level based on estimated and assessed risk. IMESAFR v2 Bundle is a specialized probabilistic risk assessment software for explosive storage facility personnel that calculates safe distances to explosive storage facilities and can determine the safety distances from explosives stores and can determine the level of safety based on the estimated risk and value.The results of the computer simulation regarding the highlighting of all the effects (risk curves, overpressure curves, contour areas regarding the design of the fragments resulting from the detonation - debris) generated by the potentially explosive site were obtained for different explosive charges in TNT equivalent. In order to carry out research on the propagation of the pressure wave during the detonation of explosive charges, on the mobile platform with the TESTES pressure sensor, an experimental assembly was carried out using explosive charges made of RIOMAX type explosive and Detonating Fuse, with the following quantities: 143g (RIOMAX cartridges) and 63g (10.5ml detonating fuse with 6g/ml explosive). contour areas regarding the design of fragments resulting from detonation - debris) generated by the potentially explosive site were obtained for different explosive charges in TNT equivalent. In order to carry out research on the propagation of the pressure wave during the detonation of explosive charges, on the mobile platform with the TESTES pressure sensor, an experimental assembly was carried out using explosive charges made of RIOMAX type explosive and Detonating Fuse, with the following quantities: 143g (RIOMAX cartridges) and 63g (10.5ml detonating fuse with 6g/ml explosive). contour areas regarding the design of fragments resulting from detonation - debris) generated by the potentially explosive site were obtained for different explosive charges in TNT equivalent.

We realized the air pressure wave visualization for the experiments with 1.143/2.286/3.429/4.572g explosive as well as for the 13ml detonating fuse with 6g explosive/ml by using the BOS (background oriented Schlieren) effect, applied to fast filming with 7000 fps and a resolution of 1024 x 768 pixels. The calculation of the peak air (shock) pressure - overpressure, generated by the TNT equivalent charge, was made knowing that overpressure is a function of distance, mass of explosive and local conditions. In order to determine the law of pressure variation in the wave front, all the data recorded with two Kistler systems, used in the experiments, were taken into account, which were synthesized in a spreadsheet, in order to determine the values of the experimental coefficients for drawing the overpressure curve.

Chapter 8 entitled *Final conclusions and personal contributions* highlights the resulting conclusions and the contributions made to the development of the methodological infrastructure for explosion risk assessment, as well as the method of implementation and capitalization of the research results undertaken, both at the current level and in the future.

5. Personal contributions

The degree of novelty and complexity of the thesis is accentuated by the growing importance of the challenges generated by the need to increase the efficiency of the management of this category of hazards, both from the perspective of the requirements of the evolving regulatory context, and from the growing awareness of the need for systemic management, systematic and integrated assessment of global risks that may severely affect all target components of industrial activity (safety of people, assets/ property, environment and business/activity itself). Dynamic risk analysis can be an emerging approach for continuous assessment and improving the landscape of systemic risks. Although it may have a number of limitations related to its reliance on data collection, it has the potential to be an important step forward in substantially improving decision support and critical risk communication

For the conceptualization and methodological-applicative development of the development phases of the doctoral research, we resorted to the collection, interpretation and use of information and knowledge, tools and techniques specific to several areas of knowledge and scientific disciplines, such as engineering and industrial security, legislation, security and occupational health, industrial management, elements of probability theory, informatics, etc.), thus ensuring a pronounced inter- and multidisciplinary character, as a necessary condition to be able to identify the most appropriate study paths and identify feasible solutions to achieve the objectives presets of the research.

5.1. Theoretical contributions

The main theoretical contributions with significant technical-scientific impact, extracted from the framework of the doctoral thesis, are:

- Carrying out an in-depth integrated analysis through which the national and international legislative framework was identified that allows the safe development of specific activities with explosive materials at the level of industrial sites in the field of civil explosives;
- Carrying out a study that highlighted the correspondence between the European Directives on the risk of major accidents and the regime of explosive substances regarding the preparation of security reports, thus creating the premises of a particularly useful guide for economic operators active in the field of civil explosives, facilitating making the optimal decisions when it is necessary for the integrated security of industrial sites intended for the manufacture and storage of dangerous products/substances of an explosive nature;
- Conceptualization of the notion of risk specific to industrial sites where operations with explosive materials are carried out;

- Development of the methodological infrastructure for quantitative assessment of the explosion risk generatedfollowing specific operations with explosive materials;
- Analysis of the criteria for the acceptability of the explosion risk generated during specific operations with explosive materials, in order to establish the main scenarios for the disposition of explosive structures (PES) and exposure (ES) at the level of industrial sites intended for specific operations with explosive materials;
- Conceptualization of the simplified fatality mechanism caused by an explosion-type event following the detonation of explosive materials;
- Development of the methodological tool for the evaluation of the mitigation effects against the explosiongenerated by overpressure and impulse in the open air;
- Development of the generalized grapho-analytical tool for the evaluation of the mechanism of damage to the human component / the structural collapse of a building affected by the explosion;
- Elaboration of the methodological tool for the assessment of the heat factor of danger generated during thedetonation of explosive materials;
- Development of the analytical tool for modeling the dispersion of material fragments generated byexplosions;
- Parallel analysis of potential fatality mechanisms and their grouping into four branches of sequential steps: ***Pressure and Impulse***(the explosion produces a blast wave described by both overpressure and impulse); ***Structural response*** (two consequences are evaluated here: the collapse of the building and the breaking of the windows – the design of the material fragments ***); Debris***- Debris (the debris branch combines the dangerous fragments resulting from the detonation of explosive materials depending on the kinetic energy); ***Thermal*** (the thermal branch is used only for Hazard Division (HD) 1.3, explosives producing mass incendiaries);
- For the most truthful modeling of the design effect of material fragments resulting from the detonation of explosive materials, the new resulting model was used, with non-zero azimuthal variation, according to which the amplitude along the central direction varies according to the classinterval of the fragments, and the standard deviation is a constant angle.

8.2.2. Experimental and applied contributions

The main experimental and applied contributions with significant technical-scientific impactderived from the doctoral thesis are:

- The identification of the peculiarities of the evaluation of the explosion risk at the economic operator investigated in the case study, with activity in the field of preparation and storage of the ANFO type explosive, which offers specialists a synthesis of the technical information of first necessity, the lack ofwhich was felt on the occasion of various unforeseen events that have occurred;
- Elaboration and analysis of the main accident scenarios that could occur at the level of the industrial site within the pilot economic operator;
- The computerized evaluation of the explosion risk of the explosion security level at the studied unit, which highlighted the need to take measures to improve the site's security and the health protection of workers in dangerous areas; Scenarios with major or catastrophic consequences were taken into account. In order to identify the worst possible accident scenario at the level of the studied industrial site, reference scenarios (hypotheses) were defined and established, highlighting for each individual case the significant aspects of configuration (scenario coding, eventtype, possible location, causes/effects, production conditions, overpressure value, effects on buildings and human health, affected area, computer modeling result, etc.), respectively:

  (B) The accident scenario regarding the explosion of a quantity of 300 kg of ETNT at Warehouse III –

staples; (C) The accident scenario regarding the mass explosion of a quantity of 1300 kg of ETNT at Warehouse III – staples; (D) Accident scenario regarding the mass explosion of a quantity of 3000 kg of ETNT at Warehouse III – AUSTINITE; (E) Accident scenario regarding the mass explosion of a quantity of 20,000 kg of ETNT at Warehouse I – LAMBREX, EMILEX, NITRAMON, AUSTINITE; (F) Accident scenario regarding the mass explosion of a quantity of 12500 kg of ETNT at Warehouse I – AUSTROGEL; (G) The accident scenario regarding the explosion of a quantity of 20,000 kg ETNT of stored ammonium nitrate due to the spread of a fire at the Ammonium Nitrate Warehouse;

- Analysis and centralization of data regarding the risk of explosion generated following the detonation of explosive materials at the investigated location (fatalities, area of major injuries, area of minor injuries, establishment of safety distances);
- Establishing general measures to prevent emergency situations specific to the analyzed industrial site.
- Carrying out computer simulations of the explosion effects produced by the detonation of explosive materials for industrial and civil applications:

a *Computerized simulation of an explosion in the case of an ISO 1C container located on an industrial site, using the IMESAFR specialized software;*

  - *Computer simulation of an explosion in front of the IGSU building, using specializedIMESAFR software.*
  - *Plotting of overpressure curves, risk curves and contour maps for the design of fragments resulting from detonation, highlighting the affected areas*: lethal zone/major damage zone/minor damage zone).

- Carrying out experimental research on the effect of blast pressure on the detonation of explosive charges for the developed pressure sensors:
  - *Open field experiments for air pressure wave on mobile platform with TESTES pressure sensor;*
  - *Visualization of the pressure wave generated by the detonation of variousexplosive charges using the PHANTOM high-speed camera.*

The obtained results have a significant potential to generate operational and security benefits for the holders of activities that have technical infrastructures for the storage/production of civil/industrial explosives, which can be capitalized in the processes of identification/ development/implementation of policies/procedures/operations carried out in such industrial sites and issuing recommendations/good practices regarding the targeting of higher security objectives. The work is primarily addressed to practitioners/specialists involved in the analysis of major explosive risks associated with industrial sites manufacturing/storing explosives, in order to establish the most effective and realistic measures to prevent/protect major risks,and the implementation of safe practices in order to ensure/guarantee increased and predictable levels of operational safety, but - at the same time - some of the results obtained can also be used by non- experts, because technical solutions are offered for computerized modeling and quantitative analysis of explosive risk .

8.2.3. Future research directions

Taking into account the contributions highlighted in the paper and the research problem identified,the following research directions can be formulated with the possibility of future approach:

- Integrated digitized monitoring of industrial sites in the field of civil explosives from the point of view of explosion risk;
- Optimizing the integrated security of industrial sites intended for specific operations with explosive materials on the basis of rational layout in compliance with the criteria of acceptability of explosive and exposure structures;
- Research on the creation of a smart industrial site equipped with state-of-the-artIT devices and specialized IT applications designed to ensure and remotely monitor its integrated security.