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Quick Assessment of Explosion Hazard in Small Premises

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Workplace safety and emergency procedures require the identification of explosion risks. For this reason, EU Directives as ATEX (Atmosphere Explosives) normative have been specifically issued, with the aims of protecting worker safety, properties, environment and population. Besides, the cited law requires strong expertise and knowledge of the complex science involved in explosion phenomena, which is not straightforward in small and medium enterprises. Indeed, a large amount of published work concerns explosion hazard in large-scale industrial environment, whereas there is a clear lack of studies concerning the risk assessment of explosion in small premises like laboratories, workshops, garages and others.
In this work, a management tool for small premises that allows the identification of explosion hazard through a rapid screening of the workplace and the recognition of a limited number of indicators, as the properties of material stored or manipulated and the adopted mitigation systems, has been developed. The tool is essentially based on the maximum quantities of flammable substances and allows the quick assessment of explosion hazard starting from the visual screening or inspection of the workplace.

1. Introduction

The occurrence of the explosion phenomenon should be always considered when evaluating the safety of workplaces where flammable or unstable solid, liquid and gaseous substances are stored or handled. This destructive phenomenon may be characterized by several effects affecting the exposed targets (workers, assets, equipment): mechanical effects (air shock, debris), thermal effects (flames), dispersion of partially oxidized and combustion products, which are often toxic. Furthermore, the explosion can trigger secondary adverse events as fires of large-scale solid or liquid combustibles, which in turn may produce cascading effects in the surrounding equipment or buildings. Fire and explosion safety in workplaces, buildings and premises is a major concern of European legislation, in particular through the ATEX Directives 1994/9/EC (1994) and 1999/92/EC (1999). The first determines the essential safety requirements for products intended for use in potentially explosive atmospheres, while the latter establishes obligations on the employer to protect the safety and health of employees potentially at risk from explosive atmospheres. The application of these Directives is demanded to the national states, but a sound application requires the knowledge of the complex chemical and physical phenomena involved, which generally cannot be found in small and medium enterprises. Just as an example, the methodology called GriSU (Grimaz and Pini, 1999), an expert system conceived for the fire safety assessment and management in historical centres, has been considered too complex for widespread application. Furthermore, there are very few studies concerning the assessment of fire and explosion hazard in small premises like laboratories, workshops, or other similar civilian system.
In this paper, a management tool that allows the identification of fire and explosion hazards through the rapid screening of the system, based on the recognition of the amount and characteristics of hazardous substances within the cited premises, has been developed. The tool aims at the preliminary assessment of safety performance of the analyzed system and may be usefully adopted for the definition of hazard maps covering the workplace and to manage the hazards by choosing among effective technical and organizational countermeasures, tailored on the specific needs of the premises, according the scheme proposed by Grimaz et al. (2014). The tool may also be useful to plan emergency response.

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2. Methodology

The methodology developed in this work is shown in Figure 1. There, two steps can be recognized. The first, defined as “Characterization”, aims at assessing if hazardous substances stored or handled in the workplace can cause an explosion. In the second step, the method evaluates the safety performance of the workplace by considering the adversity level that characterizes the workplace, through checks aimed at evaluating the degree of safety in analogy with the fire safety objectives as defined in the EU Directive 89/106/EEC (1989). The two parts are defined in details in the following.

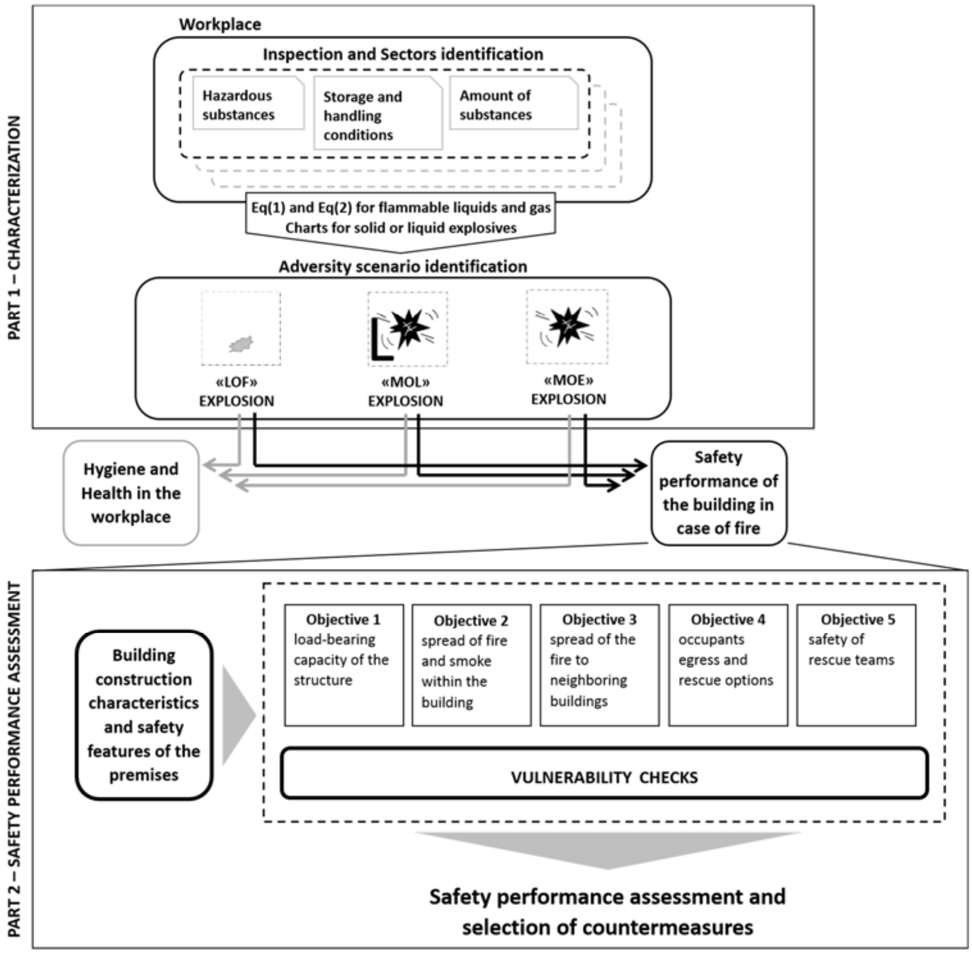

Figure 1: General overview of the method

2.1 Characterization

An explosion is characterized by several effects that can affect targets: mechanical effects (air shock, debris), thermal effects (flames), dispersion of partially oxidized and combustion products, which are often toxic. These effects are strongly dependent on the physical properties of the analyzed substance, as the combustion or the decomposition energy, and on the net amount of hazardous substance. In addition, several other hexogen characteristics and factors must be considered, for instance the structural design of the storage systems as long as the building construction characteristics and the presence of safety measures (prevention, mitigation).

The characterization process starts dividing the workplace into sectors, i.e. subsections characterized by uniform functional and operational characteristics and separated from those adjacent by separation elements such as walls and floors or - in the open - barriers or separation distances. Such elements may be more or less permeable to the adverse effects and often difficult to define. For the aims of this method, we have identified sectors according to the approach derived from the Dow Fire & Explosion Index Hazard Classification (AIChE, 1994), which is generally applied to assess risks in industrial plants. More specifically, we have adopted the definition of the Material Factor (MF), which is a measure of the intrinsic rate of potential energy release from fire or explosion produced by combustion or chemical reaction.

Table 1: Susceptibility of the storage conditions to give spills or dispersions

Storage or handling conditions	Susceptibility to give spills or dispersions	Coefficient of dispersion α
Pipes with properly maintained or without flanges, fittings, etc.. Closed and properly maintained and stored cylinders	1	0
Hermetic, non-combustible, safety containers or cabinets	2	0.2
Non-combustible containers or cabinets	3	0.7
Frangible or combustible containers or cabinets. Improperly stored and/or maintained cylinders and pipes	4	1

The MF is a function of the type of substance used only; specifically it could be determined based on the flammability and reactivity numbers of the substance, which respectively rank the flammability and reactivity (or instability) hazard of the substance. The flammability number takes into account the susceptibility of materials to burning, while the reactivity number takes into account the intrinsic susceptibility of materials to release energy. Criteria to determine flammability and reactivity numbers are detailed in NFPA 704 (2007). In general, the higher the value of the MF, the more flammable and/or reactive the material. If mixtures of materials are used, the MF is determined from the properties of the mixture. When many substances are stored or handled, the highest value of the MF is suggested. The MF is then adjusted based on the susceptibility to give spills or dispersions of storage and handling conditions. Similarly to the approach proposed in Grimaz et al. (2012) for atmospheric emissions, storage conditions are qualitatively ranked according to the idea that the higher the susceptibility, the larger the rank number (Table 1). In such a way, sectors of the workplace are identified based on the hazardous substances, independently of judgmental factors.

For the aims of the methodology, we have then defined three adversity scenarios (Table 2), which describe the potential adverse situations that could characterize the sector of the workplace in the case of explosions. In the table, an important differentiation is based upon the value of maximum pressure produced by explosion. To this regard, it is worth mentioning that many literature approaches relate the explosion consequences to the maximum peak static overpressure only (e.g. Cozzani et al. 2006, Baker et al. 1983). According to Mannan (2005) and Cozzani et al. (2007) this option gives conservative results. Furthermore, the overpressure limit of 3 kPa corresponds to minor damages in many essential textbook (CCPS, 1996, TNO, 1992).

Table 2: Definition of conventional adversity scenarios

Adversity Scenario	Description
Limited Overpressure and Fire (LOF)	Presence of small amount of hazardous substances, which may give localized fires and small explosion with peak overpressures lower than 3 kPa both in the near and far field and negligible debris or fragmentation. Flames or fires are local with negligible dispersion of smoke and reaction products.
Major Overpressure and Fire – Local effect (MOL)	Presence of relevant amount of hazardous substances which may give localized or generalized phenomena of rapid combustion or fast decomposition, with the development of peak overpressures higher than 3 kPa in the near field, hence with limited and localized effects. Low velocity fragments or debris may be produced. Flames or fires are local with some dispersion of smoke and reaction products but near the explosion source.
Major Overpressure and fire – Extended effect (MOE)	Presence of relevant amount of hazardous substances which may give generalized phenomena of rapid combustion or fast decomposition with the development of heat and peak overpressures greater than 7 kPa, which may affect the entire volume, induce the structural collapse and possibly extend related effects outside the analyzed system due to shock waves, debris and flames either directly (impingement) or due to heat radiation. Toxic reaction products may be generated in large amount.

Overpressures in the order of 7 kPa are quoted as sufficient to cause structural damage to process equipment and walls (Salzano et al., 2013).

Other adversity effects are the presence of large amount of toxic by-products, the debris formation and the flames, either directly connected to the direct combustion reaction during the explosion or due to solid or pool fires originated by the primary scenario (the explosion), which in turn may produce cascading effects in the surrounding equipment or buildings.

The explosion overpressures are evaluated taking into account the type and amount of hazardous substances actually present inside the analyzed sector of the workplace. More in detail, when the source of potential explosions are flammable liquids or flammable gases the adiabatic mixing model proposed by Olge (1999) is adopted to evaluate the peak overpressure. Eq(1) and Eq (2) allows the calculation of the peak pressure (P_f) given the enclosure volume (V_r), the initial enclosure pressure (P_i), the initial volume of the fuel-air mixture (V_b) and the expansion factor (E) of the stoichiometric fuel-air mixture, which for most hydrocarbon fuels is in the order of 8 to 9. It could also be approximated as the ratio of the fuel adiabatic flame temperature to the initial temperature.

$$P_f = \frac{P_i}{V_r}\left((V_r - V_b) + EV_b\right) \tag{1}$$

$$V_b = \min\left\{V_r;\ \alpha V_f\left(\frac{100}{X_{st}}\right)\right\} \tag{2}$$

In Eq(2), the volume of the fuel-air mixture (V_b) is calculated given the total amount of fuel (V_f) and the stoichiometric concentration of fuel in percent (X_{st}). Here it has been introduced the coefficient of dispersion (α) that represents the fraction of the total volume of fuel which it could be dispersed due to storage conditions (Table 1). In the case of solid or liquid explosives the UFC 3-340-02 (2008) and more recently, the works of Salzano et al. (2009), Basco el al. (2010) and Salzano and Basco (2012) provide useful charts relating the ratio of enclosure volume over explosive volume (TNT and others) to the maximum pressure developed inside the enclosure. Once the adversity scenario that characterize the sector has been identified, it is possible to proceed on the one hand to assess compliance with health and hygiene requirements in the workplace according to specific standards or procedures and on the other to assess the safety performance of the building.

2.2 Safety performance assessment

The ATEX Directives aim mainly at improving health and safety in the workplace in order to reduce injuries and deaths among workers due to explosive atmospheres but are not addressed to the performance assessment of the building and more in general fo small premises in the case of explosion. For such a purpose, the EU Directive 89/106/EEC (1989) defines five objectives for the essential requirement number 2 – safety in case of fire - that construction works must comply. These objectives deal specifically with fire and smoke but can be usefully adopted for explosion, if considering that an explosion is characterized by thermal effects (flames) and dispersion of partially oxidized and combustion products and that an explosion can trigger secondary adverse events, such as fires. The main objectives to be considered in order to assess the safety performance of the premises are then:

1) The load-bearing capacity of the construction. The stability of the main structure in case of fire or explosion is necessary in order to provide for occupant, rescue teams and fire-fighters safety.

2) The generation and spread of fire and smoke. The aim of this objective is to limit the spreading of the effects of a fire inside the building; in the case of an explosion, this objective can be also read as a limitation to the propagation of pressure wave and combustion products in other zones of the workplace where sensible targets may be present.

3) The spread of the fire to neighboring construction. The aim of this objective is to limit the spreading of a fire towards adjacent buildings and premises; in the case of an explosion, this objective can be interpreted also as a limitation of the effects of explosions, particularly overpressures.

4) Occupants escape or rescue options. Means of egress for occupants and access for rescue teams is necessary to allow occupants within the premises to be able to evacuate in safety place, or be rescued by firefighters or rescue teams.

5) The safety of rescue teams. In addition to load-bearing capacity, limitation of spread of fire and smoke and evacuation of occupants, rescue operations and fire-fighting must be carried out efficiently however with a reasonable level of safety, either within or in the surrounding of the premise.

The safety performance of the workplace is then assessed with respect to these five objectives through simple checks. Each check assesses the compliance with a specific objective taking into account adversity level as defined in the characterization and the construction characteristics and the safety features of the workplace, based on three levels of judgment: A, B and not passed. If the check is passed in class A or B the workplace complies with the specific objective assessed. If the check is passed in class A, the workplace has a great

safety margin with respect to a class B. On the contrary, if the check is not passed, the workplace does not comply with the specific objective and countermeasures must be taken in order to remove the threat. More in detail, in the proposed method we focused on the first three objectives, while the compliance with objective 4 can be assessed through the PASS method (Grimaz and Tosolini, 2013).
The following section gives some insight on the methodology through an example case.

3. Example case

The application and utility of the proposed method is illustrated with an example. From the inspection of a workplace, it emerged that within an office room, solvents used for cleaning and maintenance of instruments are stored. The room volume is nearly 70 m^3. The inspection and the analysis of the safety data sheets have shown that about 8 liters of toluene, the hazardous substances, were stored, at ambient conditions, in plastic containers in an open cabinet. Following the procedure, the office room is first characterized based on the flammable substance characteristics (toluene: flammability number = 3; reactivity number = 0; MF = 16; E = 8.5; X_{st} = 2.3 %) and on the storage conditions (susceptibility to give dispersions = 4). Following from Table 1 and Eq(2), all the toluene is considered to form a flammable mixture according the adiabatic mixing model. According to Eq(1) the maximum overpressure inside the room is 3.9 kPa. Therefore, according to Table 2, the adversity scenario that characterizes such sector of the workplace is MOL, which according to Figure 1, requires a safety performance assessment of the building. Further inspection showed also that the premise is designed as a reinforced concrete frame-type structural system. Both interior and exterior nonbearing walls are instead unreinforced masonry walls. The strength of each element is then assessed considering the possible failure mechanisms due to the action of the overpressure, assumed evenly distributed on the element and taking into account restraints as well as geometrical and material properties of the element analyzed. The dynamic effect of the rate of pressure rise is taken into account through a Dynamic Load Factor (Biggs, 1964; NFPA68, 2007). Table 3 summarizes the results of the checks performed. It shows that the improper storage of toluene inside the office room may give rise to severe consequences.

Table 3: Checks performed to assess the compliance with the EU Directive 89/106/EEC objectives

Objective	Description
1. Load-bearing capacity of the structure	From a simple structural analysis, it emerges that the floors are the most vulnerable parts of the structural system. The composite cast-in-place RC and masonry floors are characterized by an ultimate positive moment of 20 kNm and by an ultimate negative moment of 6.5 kNm. Such values are sufficient to withstand the calculated overpressure, therefore the check is passed.
2. Spread of fire and smoke	The check aims at assessing: 1) if the physical barriers (e.g. interior walls) that enclose the sector are able to withstand the calculated overpressure and 2) whether frangible elements, i.e. the elements that are specifically designed for venting and the elements with a strength smaller than 3 kPa, are placed indoor or in a way they could collapse or discharge adverse effects towards areas with sensible targets. According to a structural analysis, interior nonbearing walls have a strength of 1 kPa that is smaller than the calculated overpressure. Furthermore, such wall could collapse towards a corridor where people may be present. For this reasons the check is not passed.
3. Spread of the fire to neighboring construction	The building is detached, the separation distance with the nearest building is about 15 m. The external infill walls have a strength larger than the calculated overpressure; the windows could generate glass fragments. The check is passed.

4. Conclusions

In the paper, a simple method for the quick assessment of explosion hazard in small premises such as laboratories, workshops and others is presented. The method is divided in two main parts: in the first the workplace explosion hazard is characterized by taking into account the type and the amount of hazardous substances stored or handled, whereas the second part is the performance assessment of the analyzed building or premises. The explosion hazard is described trough three different adversity scenarios, which allow to describe the potential emergency situation to deal with. Once the adversity scenario has been identified it is possible to proceed with the second part of the method that allows a preliminary assessment of the safety performance of the workplace through a set of simple checks. For such a purpose, the fire safety objectives defined in the EU Directive 89/106/EEC have been adopted. Such a method could be usefully adopted for the definition of hazard maps covering the workplace and to manage the hazards by choosing among effective technical and organizational countermeasures.

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