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Ph.D. Dissertation

Innovation Driven by Human and Organizational Factors (HOF) in Risk Assessment Methodologies and Standards: ATEX (Explosive Atmosphere) Risk Assessment Application

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Sincerely,

Jie Geng (Jane)
Turin, Italy

ABSTRACT

ATEX (explosive atmosphere) risk assessment is required when any equipment or system potentially causes explosive atmospheres. Despite many operations on plant and equipment containing dangerous substances are performed by operators, influences of human and organizational factor (HOF) are mostly neglected. This research work, according to the overview of the general risk assessment and human factor integration techniques, focuses on the HOF influence on a specific application domain: the ATEX (explosive atmosphere) risk assessment domain. The integrated ATEX risk assessment methodology with HOF is proposed. The ATEX-HOF methodology provides a quantitative risk analysis approach with taking into account of HOF. Inside each phase, clearly assessment goals are identified which are enable to conduct the ATEX risk assessment with simplified 'step-by-step'. An event tree based probabilistic assessment has been introduced, which is taking into account both the technical barrier failure (Pr_{tbf}) and the human intervention (e.g. operational failure, and/or operational barrier failure) in terms of Human Error Probability (HEP). Hence, the ATEX-HOF risk assessment becomes more complete than the traditional approach.

Two on-site applications shown how taking into account HOFs is particular important in companies where the safety culture is lower and consequently the usual hypothesis of the correctness of operator intervention (in maintenance, normal operations, and emergency) could bring to not conservative results. The applied operational (HOF) barriers explicated in the analysis can be used to support for defining a more detailed set of operational procedures, which is able to maintain the risk level evaluated.

In addition, since several accident investigations have found that 80% correspond to human error, in nowadays, the change in safety has focused on developing good safety cultures that positively influence human behaviour at work to reduce errors and violations. HOF as the major consideration within the safety culture plays an important role in the Safety Management System (SMS). Safety culture is not a difficult idea, but it is generally considered as "trust", "values" and "attitudes", which is difficult to clarify the meaning in practise. The Event tree based probabilistic assessment method has been introduced to quantify the HOF influence. This research, hence, can be concerned as an attempt to handle safety cultures in practice via the integration of the risk assessment.

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SCOPE OF THE RESEARCH

I. About the INNHF Project

This research work forms part of the EU FP7 funded Marie Curie Actions Initial Training Networks research project titled Innovation through Human Factors in Risk Analysis and Management (INNHF - FP7-PEOPLE-2011-ITN: Project ID 289837).

The aims of the project INNHF are (www.innhf.eu): "

1) to offer a multidisciplinary training in the field of risk assessment and maintenance management integrated with human factors, in tight contact with companies and universities within this consortium;
2) to strengthen and structure initial training of researchers in system engineering at European level;
3) to attract students to scientific careers;
4) to provide trained researchers with the necessary skills to work in industry; and,
5) to improve career perspectives by broad skills development. "

S&T objectives of the research programme are:

The **INNHF main objective** is to formalize an approach and make it possible to integrate the current and developing assessment methods recommended or required by recognized industrial standards and methodologies, with an easy to use but complete human factors and system health management approach.

II. Objectives and Roadmap of This Research

ATEX (Explosive Atmosphere) Risk Assessment is required when any equipment or system potentially causes explosive atmospheres. Despite many operations on plant and equipment containing dangerous substances are performed by operators, influences of human and organizational factor (HOF) are mostly neglected (e.g. maintenance activities, operational barriers, and other operational activities, etc.). This research work, according to the overview of the general risk assessment and human factor integration techniques, focuses on the HOF influence on a specific application domain: the ATEX (explosive atmosphere) risk assessment domain. It aims to propose an advanced methodology, in order to analyse the HOF influence on ATEX hazards. The roadmap of this research was followed:

Stage 1. Introduction & Background Information Collection: With the review of current risk assessment relevant standards and the conducting the interviews in current industries, a question occurs: “Are current safety standards and their suggested risk assessment methodologies enough to apply without considering human and organizational factors (HOF)?” (Chapter 1)

Stage 2. Literature Review: Current risk assessment methodologies suggested by standards and human factor integration (HFI) techniques were reviewed, in order to find a way to integrate HOF into the risk assessment methodology. (Chapter 2)

Stage 3. The ATEX-HOF Methodology Development: Relevant ATEX risk assessment methodologies were focused, with the aim of working on the current safety culture and human factors interventions, hence, an advanced methodology was proposed to analyse HOF influences on ATEX hazards. (Chapter 3 & 4)

Stage 4. Application: Two applications of the ATEX-HOF Methodology were conducted (one is in a food industry and another is in an automotive industry) were conducted. Meanwhile, the comparison of the traditional and ATEX-HOF Methodology was conducted, in order to see the performance of the ATEX-HOF Methodology, and improve the methodology. (Chapter 5, 6, & 7)

Chapter 1. Introduction

Are current safety standards and their suggested risk assessment methodologies enough to apply without considering human and organizational factors (HOF)?

Chapter Outline:

1.1 Background
1.2 A Need for a Standard
1.3 Risk Assessment and Its Relevant Standards
1.4 Human and Organizational Factors (HOF)
1.5 Interview: Current Risk Assessment Standards Applied in Industries
1.6 Discussion

Chapter 1. Introduction

1.1 Background

Start from July 2003, EU organizations must follow the directives to protect employees away from explosion risks under potential explosive atmosphere environment. Two ATEX directives were proposed:

- the ATEX 95 equipment directive 94/9/EC, Equipment and protective systems intended for use in potentially explosive atmospheres; the ATEX 94/9/EU has updated and will be removed and replaced by a new Directive 2014/34/EU, which will be mandatory for manufacturer in 2016.

- the ATEX 137 workplace directive 99/92/EC, Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

As the requirement from ATEX directives,

> *"It is the duty of Member states to protect, on their territory, the safety and health of persons and, where appropriate, domestic animals and property and, in particular, that of workers, especially against the hazards resulting from the use of equipment and systems providing protection against potentially explosive atmospheres."*
>
> *"In view of the nature of the risks involved in the use of equipment in potentially explosive atmospheres it is necessary to establish procedures applying to the assessment of compliance with the basic requirements of the Directives." (Directive 94/9/EC*, 1994)

ATEX (explosive atmosphere) risk assessment is designed for the workplace safety and is required where any equipment or protective systems are intended for use in potentially explosive atmospheres.

The directive 99/92/EC has been referred, which lays down minimum requirements for the safety and health protection of workers potentially at risk from explosive atmospheres. For the prevention of and protection against explosions, the employer shall take technical and/or organizational measures appropriate to the nature of the operation, in order to:

- prevent the formation of explosive atmospheres, or where the nature of the activity does not allow that,
- avoid the ignition of the explosive atmospheres, and
- mitigate the detrimental effects of an explosion so as to ensure the health and safety of workers.

For assessment of explosion risks, at least it is taking account of: “

- the likelihood that explosive atmospheres will occur and their persistence,
- the likelihood that ignition sources, including electrostatic discharges, will be present and become active and effective,
- the installations, substances used, processes, and their possible interactions,
- the scale of the anticipated effects. ”

The ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures; and it is mainly referred to two standards: IEC 60079-10-1 (for explosive gas atmosphere, 2008) and IEC 60079-10-2 (for explosive dust atmosphere, 2009). For specific applications, different countries developed dedicated guidelines, as in Italy CEI 31-35 (2012) and CEI 31-56 (2007). These standards and guidelines provide procedures to evaluate the likelihood to have explosive atmosphere in the workplace.

Ignition source assessment is the second step to go through if the zone classification is determined as a dangerous zone. EN 13463-1 (2009) is a standard for Non-electrical Equipment for Use in Potentially Explosive Atmospheres. The standard aims to provide the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres. Following the procedure, the equipment can be verified and marked with ATEX markings for the further use in different ATEX zones’ working environment. EN 13463-1 covers most common ignition sources and explicates the method to identify and assess the likelihood to have 13 ignition sources listed in EN 1127-1 (2011).

Consequence analysis deals with the potential impact of the explosion scenario on human, environmental and equipment. Different ATEX risk assessment methods reviewed have different focuses: such as estimation of the overpressure and the distance from the source, the exposure of workers, the level of human harm, etc.

As mentioned above, the following standards are mainly applied among conducting the ATEX risk assessment:

- **IEC 60079-10-1**, 2008, Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres.
- **IEC 60079-10-2**, 2009, Explosive atmospheres - Part 10-2: Classification of areas - Explosive dust atmospheres.
- **EN 1127-1**, 2011, Explosive atmospheres - explosion prevention and protection - Part 1: Basic concepts and methodology.
- **EN 13463-1**, 2009, Non-electrical equipment for use in potentially explosive atmospheres.

However, when reviewing the ATEX risk assessment procedures, despite many operations on plant and equipment containing dangerous substances are performed by operators, the influence of human and organizational factors (HOF) are neglected (e.g. maintenance activity).

Hence, a questions occurs: "Are current safety standards and their suggested risk assessment methodologies enough to apply without considering human and organizational factors (HOF)?"

1.2 A Need for a Standard

> *"A **STANDARD** is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose" (www.iso.org).*

Some common principles are considered for standards in the development (www.iso.org): a) standards respond to a need in the market; b) standards are based on expert opinions; c) standards are developed through a multi-stakeholder process; d) standards are based on a consensus.

There are standards at international and national level that cover a big range of applications. ISO (International Standardization Organization) is a worldwide network of standardization organisations. ISO prepares and publishes international standards, ensuring that products and services are safe, reliable and of good quality. For electro technological standardisations there is another worldwide organisation, IEC (International Electrotechnical Commission) that deals with electrical, electronic and related technologies. ISO and IEC are in close collaboration on all matters of electrotechnical standardization. In European level there is the CEN (European Committee for Standardization), which is a group of standardisation organisations that provide standards for EU and future EU member states. Each EU member has also its own Standardisation organisation for national standards and legal purposes (INNHF Work Package 3, 2013).

1.3 Risk Assessment and Its Relevant Standards

The definitions of "hazard" and "risk" referred to the work of Health and Safety Authority (2006):

> *"**HAZARD** in general means an event or anything that can cause harm (e.g. dangerous chemicals, electricity, working at heights, etc.).*
>
> ***RISK** is the likelihood, great or small, that someone will be harmed by the hazard, together with the severity of harm suffered. Risk also depends on the number of people exposed to the hazard."*

Risk assessment provides an understanding of risks, their causes, consequences and their probabilities (Figure 1.1, ISO/IEC 31010: 2009). Specifically, risk identification answers the question *what can happen and why, and the potential consequences?* Risk analysis answers the questions *what is the probability or the severity of consequences? And what is the level of the risks?* Risk evaluation answers the question *is the level of risk tolerable or acceptable (ALARP), and does it require further mitigation control?* Last 20 years, many risk assessment techniques have been developed to undertake risks on an industrial plant (Tixier et al., 2002; ISO/IEC 31010, 2009; and Marhavilas et al., 2011).

*"**RISK ASSESSMENT** is a careful examination of what, in the workplace, could cause harm to people, so that the employer can weigh up whether he or she has taken enough precautions or should do more to prevent harm" (Health and Safety Authority, 2006).*

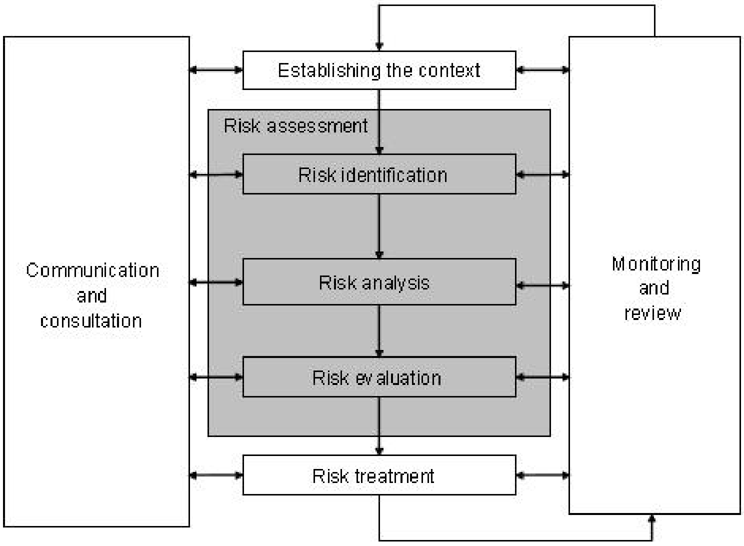


Figure 1.1 Risk assessment in the risk management process (ISO/IEC 31010: 2009)

ISO 31000:2009, ISO Guide 73:2009 and ISO/IEC 31010:2009 are the three relevant standards for all sectors, provide general guidelines and techniques for organizations of safety management plan design (ISO 31000), and the framework, procedure, and techniques of risk assessment (ISO/IEC 31010). These standards provide the background and basic principles of the risk management and risk assessment techniques.

Risk assessment process generally divided into risk identification, risk analysis, and risk evaluation (ISO/IEC 31010:2009). Controlling risk is the control of the likelihood or probability and the consequences of a given hazard causing a particular level of loss of damage (Alexander, 2000).

ISO 31000:2009, Risk management – Principles and guidelines, provides principles and generic guidelines on risk management, which can be used by any public, private or community enterprise, association, group or individual. It is not specific to any industry or sector and can be applied to any type of risk. These generic guidelines are not intended to suggest uniformity and certification of risk management across organizations. The design and implementation of risk management plans and frameworks will need to take into account the varying needs of a specific organization.

ISO Guide 73:2009, Risk management – Vocabulary, complements ISO 31000 by providing a collection of terms and definitions relating to the management of risk.

ISO/IEC 31010:2009, Risk management – Risk assessment techniques, focuses on risk assessment. Risk assessment helps decision makers understand the risks, identify risks, analyze risks, and evaluate risks, in order to provide the valuable decision of risk control. ISO/IEC 31010:2009 focuses on risk assessment concepts, processes and the selection of risk assessment techniques.

Apart from those standards, there are other safety and risk assessment related standards that focus on specific application domains, such as ISO 22000 for the food safety management, IEC 60079 series for the explosive atmosphere risk assessment, IEC 61508 series for the function safety of electrical safety-related systems, ISO 14121 series for the safety of machinery, IEC 61511 series for the function safety of safety instrumented systems for the process industry sector, and so on.

1.4 Human and Organizational Factors (HOF)

1.4.1 HOF in the Lifecycle of a System

Risk Identification is the process of finding, recognizing and recording risks, which establishes the bases of the risk analysis (ISO/IEC 31010:2009). The objective is to reveal all possible potential hazards that exist in a system or organization. The whole risk assessment would be affected if the risk identification is not conducted properly. In the industry fields, a system could be designed for a manufacturing industry, a process industry, a power plant, etc. Parnell, et al. (2010) used the definition of "system" from INCOSE (http://www.incose.org):

> ***A system*** *is "an integrated set of elements that accomplishes a defined objective. These elements include products (hardware, software, firmware), processes (policies, laws,*

> *procedures), people (managers, analysts, skilled workers), information (data, reports, media), techniques (algorithms, inspections, maintenance), facilities (hospitals, manufacturing plants, mail distribution centers), services (evacuation, telecommunications, quality assurance), and other support."*

Systems are dynamic that the passage of time affects their elements, functions, interactions, and value delivered to stakeholders. The concept of "system life cycle" was described with dynamic behaviour:

> ***A system life cycle** is "a conceptual model that is used by system engineers and engineering managers to describe how a system matures over time. It includes each of the stages in the conceptualization, design, development, production, deployment, operation, and retirement of the system elements (Parnell, et al., 2010)."*

The identification of risks in a system is finding, recognizing and recording potential hazards within a system life cycle. Here is a simple machine manufacturing system life cycle (Figure 1.2):

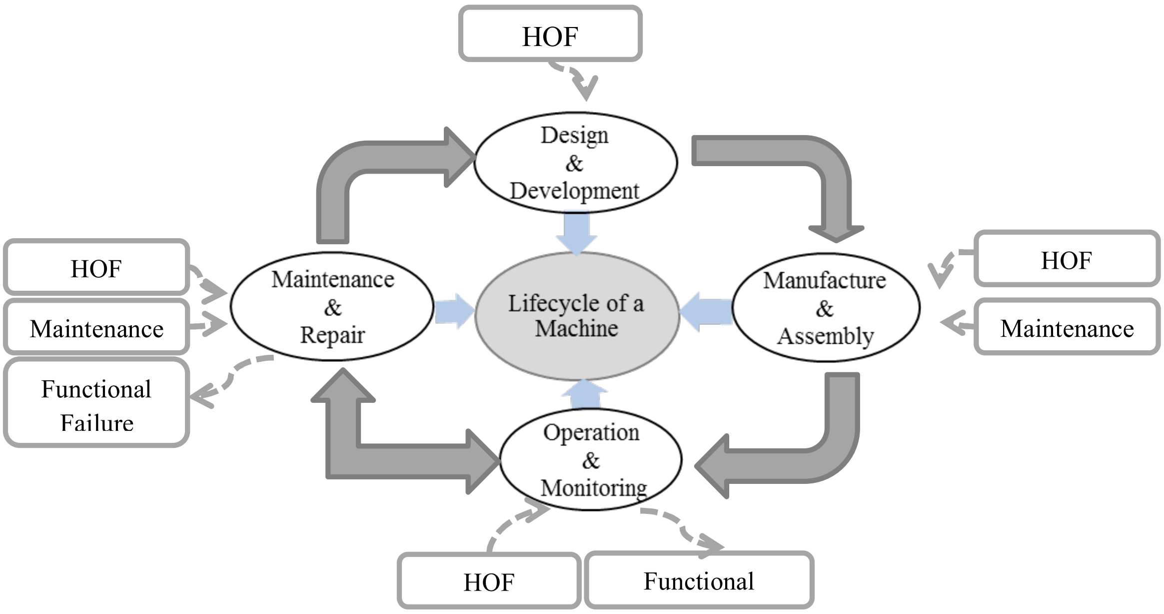


Figure 1.2 Three risk factors within a system life cycle

As mentioned in IEC 60204, machinery / machine defines as "*assembly of linked parts or components, at least one of which moves, with the appropriate machine actuators, control and power circuits, joined together for a specific application, in particular for the processing, treatment, moving or packing of a material".* From SKF Annual Report (2010), a machine's lifecycle has been expressed as the phases of "design and development", "manufacture and assembly", "operation and monitoring", and "maintenance and repairing"; afterward, given to the feedback from the "maintenance and repairing", the system goes back to the "design and development" phase for the further improvement. In each phase of a machine's lifecycle, three risk factors have been identified: system function, human and organizational factor (HOF), and maintenance. Those three factors can influence the life of a machine (enlarge or reduce its life).

Among the lifecycle of a machine, its **functional failure** may be original from the inappropriate design, incorrect manufacture, assembly, installation, and/or the incorrect operation. Functional Failure depends on whether a system or equipment is operating correctly in response to its inputs (IEC 61508-1, 2010). It is always considered among the whole lifecycle of a machine, and almost all the safety relevant standards are concerning of the functional performance, such as ISO 14121, IEC 61508, IEC 61511, IEC 62061, etc.

Maintenance typically is a management plan and a range of activities performed by humans to "*ensure the ability to maintain equipment or structures in, or restore them to, the functional state required by the purpose for which they were conceived"* (IEC60300, 2003). Equipment, even well designed, will not remain safe or reliable if they are not maintained (Baraldi, 2013). Maintenance could make its main effects on the phase of "manufacture and assembly", and the phase of "maintenance and repair". Well designed and performed maintenance plan will reduce the probability of occurrence of potential hazards from equipment failure, and further directly influence the result of risk assessment. Therefore, it is necessary to identify hazards also arise from incorrect maintenance plan and activities during the risk assessment process.

The third identified risk factor is **Human and Organizational Factors (HOF)**. HOF influences among the whole machine's lifecycle while the machine is designed, manufactured, assembled, operated, monitored, and improved. For many researchers the terms - "*Ergonomics*" and "*Human Factors*" are and should be used as synonymous. Others emphasize that ERGONOMICS (originally developed in Europe) is strongly grounded on biological sciences, with the research emphasis put on equipment and workspace design according to human needs, in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, and systems in order to make them compatible to the needs, abilities and limitations of people. Whereas **HUMAN FACTORS** (first emerged in the USA) has its scientific roots grounded in psychology, putting much emphasis on the integration of human considerations into the total system process (International Ergonomics Association, 2000). Human Analysts contribute to the human risk assessment, in order to identify, analyse, evaluate and control hazards potentially caused by human in a system.

1.4.2 HOF within Safety Management System (SMS)

Organizational culture is well known as the critical influence on an organization’s success or failure. Safety culture, as being fundamental to an organization’s ability, aims to manage safety-related aspects of its operations – successfully or otherwise (Glendon & Stanton, 2000). Several accident investigations have found that 80% correspond to human error and 20% correspond to technical failures (Reason, 1997; Hale & Glendon, 1987). The root cause of such disasters was the failure of existing Safety Management Systems (SMS, Reyes & Beard, 2001).

Senior management develops a top-down driven strategy on safety as part of an organisation's overall strategy for business or other mission. A key aspect is a SMS, which includes safety performance measurement, risk assessment and control, human resource management and safety culture (Figure 1.3, Glendon & Stanton, 2000). Within the SMS, safety culture that causes human factor interventions generally considered as “trust”, “values” and “attitudes”, which is difficult to clarify the meaning in practise (HSE, 2016). Now, the change in safety has focused on developing good safety cultures that positively influence human behaviour at work to reduce errors and violations (HSE, 2016).

Risk assessment, as another component within the SMS, permit an exhaustive identification of potential hazardous sources to prevent accident scenarios and to assess potential impact on human, environmental and equipment. However, when reviewing relevant risk assessment methods, instead of human that is dealing with the consequence analysis (the level of human harm, the exposure of workers, etc.), the HOF influence on identified hazards are less considered, even in some risk assessment that is neglected factor.

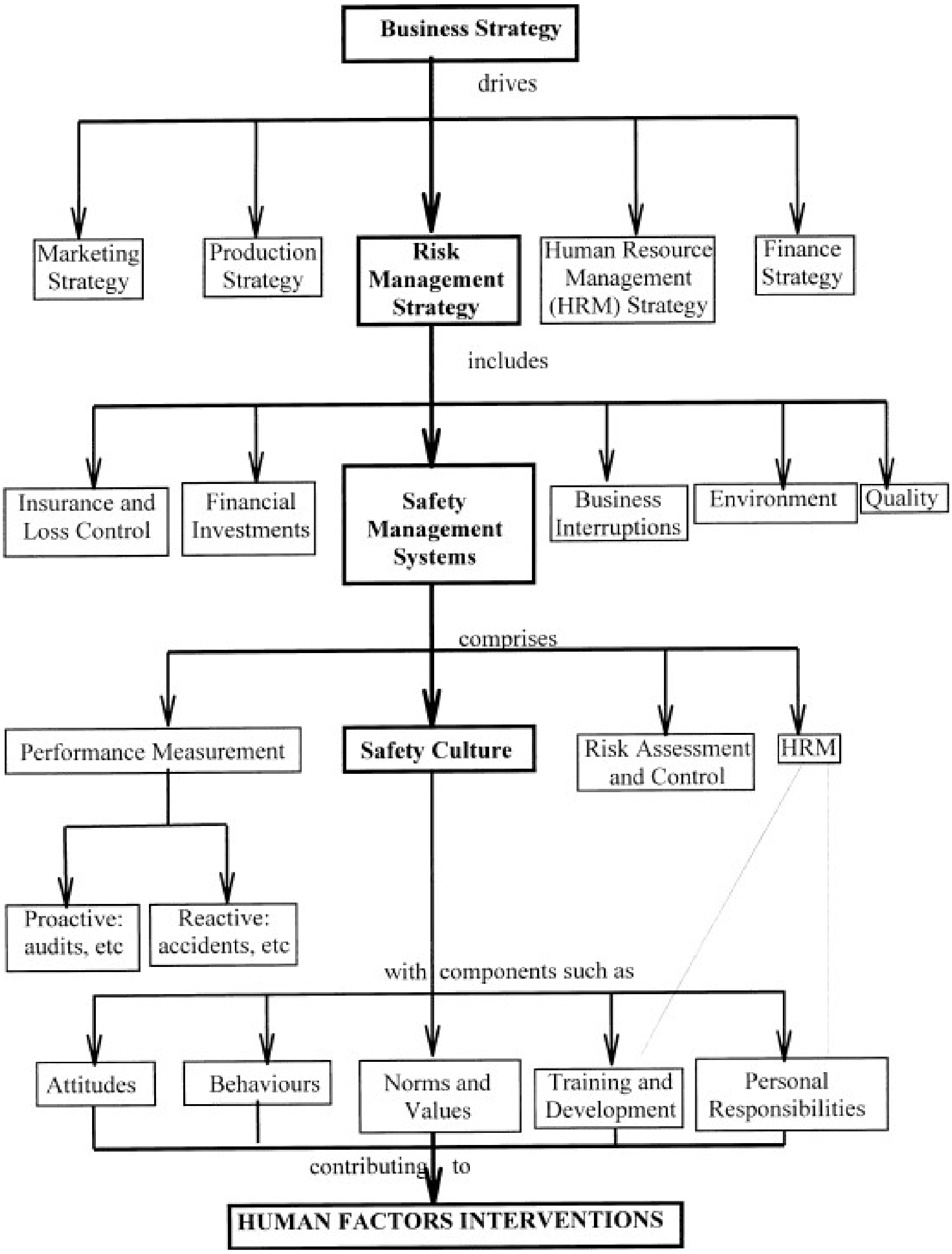


Figure 1.3 A strategic (top down) approach to safety (Glendon & Stanton, 2000)

1.5 Interview: Current Risk Assessment Standards Applied in Industries

The European Project INNHF (www.innhf.eu, 2012-2015) aims to formalize an approach and make it possible to integrate the current risk assessment methods recommended (or required) by recognized industrial standards and methodologies, with an easy to use but complete human factors and system health management approach. In the INNHF Work Package 4, the interviews were conducted in order to understand the current safety management in industries. 16 industries took part in the interviews by INNHF fellows, which include 8 process engineering and chemical industries, 2 of nuclear or energy engineering, 2 of mechanical or automotive engineering, 3 consultancies, and 1 regulator. The majority of the responses were from the process industry. The interviews have shown that usually a group or a HSE department, which integrates Safety, Health, and Environment together, take a responsibility of the safety culture within an industry. Different industries applied different standards or regulations to support their safety management systems (from international standards, national standards or regulations, to their own regulations).

1.5.1 Standards Used to Support Risk Assessment in Industries

According to the interviews, the industries have to follow the national regulations first in their safety management system (SMS). Meanwhile, they can also apply other standards to support SMS. During the interview recordings, 12 out of 16 industries (75%) prefer to follow international standards; 6 out of 16 industries (37.5%) consider national standards; 5 out of 16 industries (31.25%) consider specific industry standards; and 4 out of 16 industries consider their own regulations (Figure 1.4). **The international standards** are the most preferred. **OHSAS 18001, ISO 14001, ISO 9001 and ISO 31000** are the standards that most industries prefer to obey as their foundation of the safety management system (Figure 1.5).

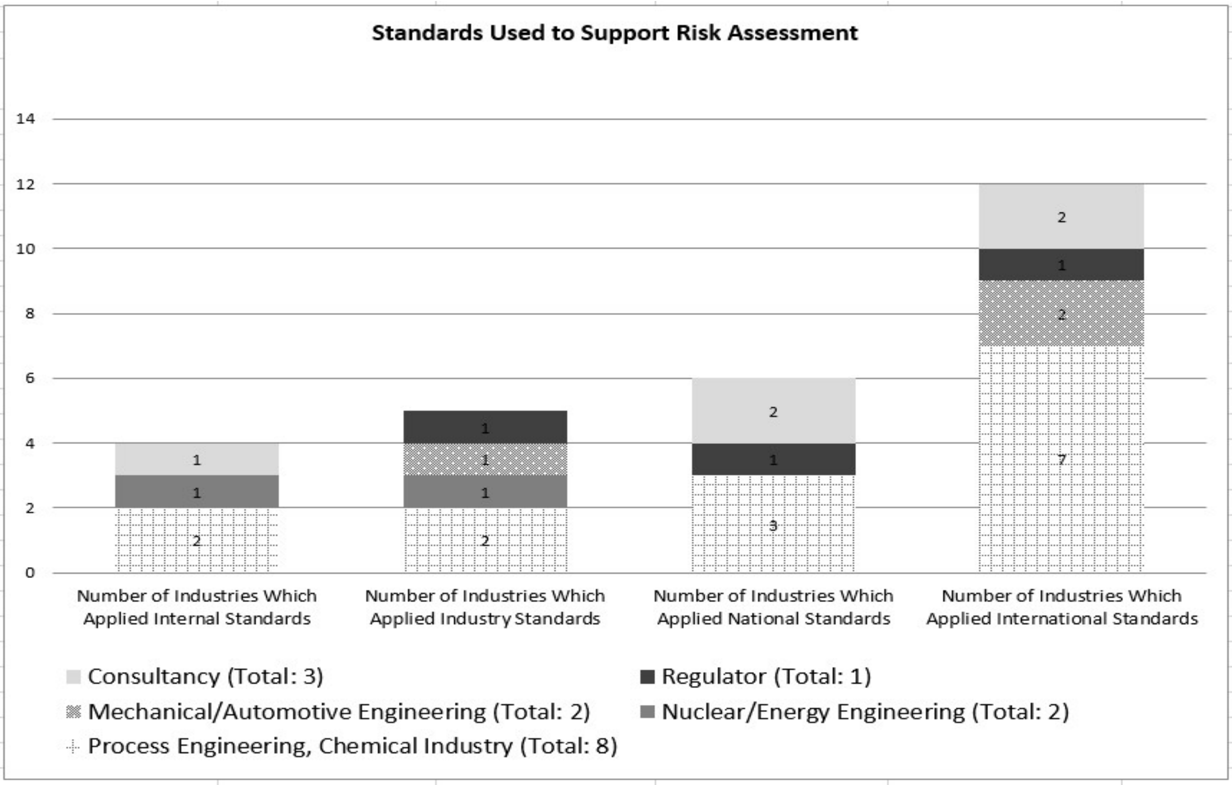


Figure 1.4 Standards applied to support the Risk Assessment

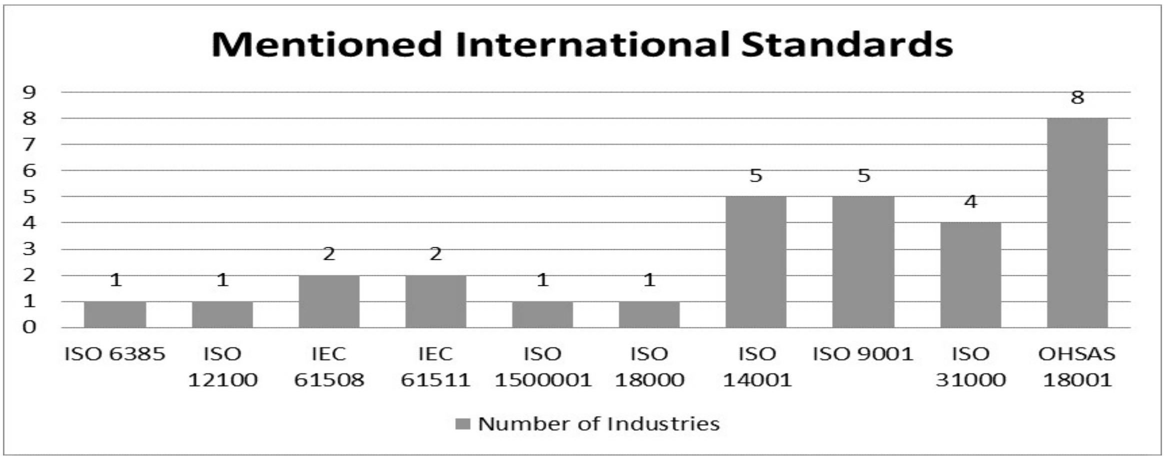


Figure 1.5 International Standards Mentioned by Interviewed Industries

1.5.2 Triggers for Risk Assessment

Seven triggers for risk assessment are collected from the interview recordings, in order to understand the triggers for companies to conduct the risk assessment.

- laws & regulations request
- safety of work
- project management
- near-miss
- changes of equipment, project, or process
- periodic review
- personal experience

Figure 1.6 shows that **"laws & regulations request", "safety of work", and "changes of equipment, project, or process"** are the top three considerations among industries.

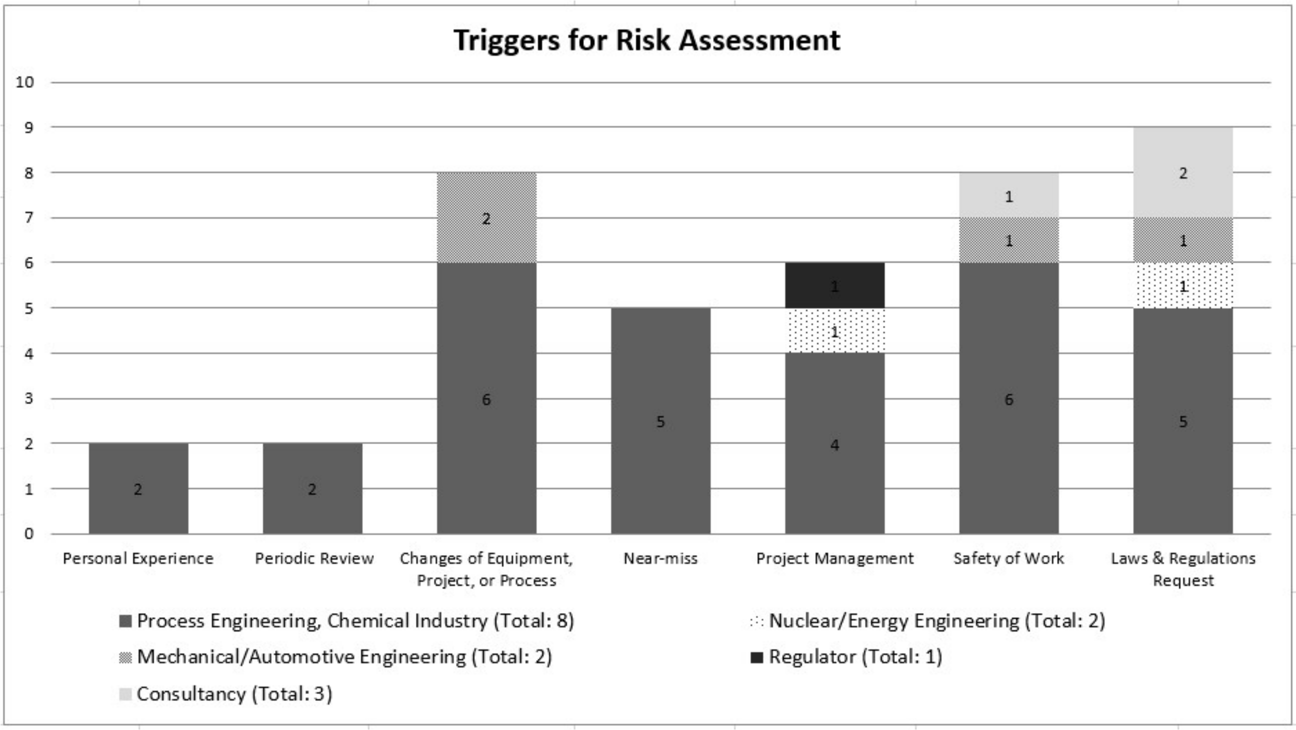


Figure 1.6 Triggers for Risk Assessment

1.5.3 Focus of Risk Assessment

Figure 1.7 shows that **"occupational health and safety"**, **"process safety"**, and **"environmental safety"** are the top three important focuses for companies conducting risk assessment.

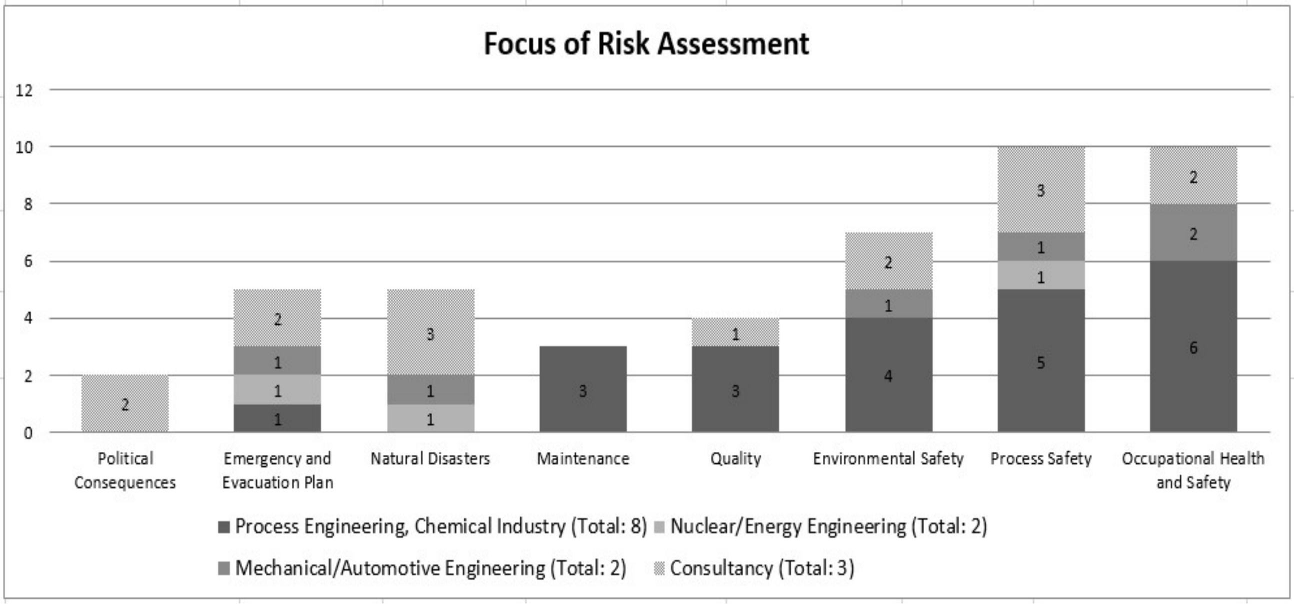


Figure 1.7 Focus of Risk Assessment

As a summary, from the 16 interviewed industries, the results have shown that all sectors use standards to support their risk assessment and safety management. The international standards most used were OHSAS 18001, ISO 9001, ISO 14001, and ISO 31000. No human factors standards were mentioned by any interviewee.

1.6 Discussion

ATEX (Explosive Atmosphere) Risk Assessment as a specific application domain, the procedures given to the relevant standards were reviewed. Despite many operations on plant and equipment containing dangerous substances are performed by operators, the influence of human and organizational factors (HOF) are neglected (e.g. maintenance activity).

ISO 31000:2009, ISO Guide 73:2009 and ISO/IEC 31010:2009 are the three relevant standards for all sectors, provide general guidelines and techniques for organizations of safety management plan design (ISO 31000), and the framework, procedure, and techniques of risk assessment (ISO/IEC 31010). Apart from those standards, there are other safety and risk assessment related standards that focus on specific application domains, such as ISO 22000 for the food safety management, IEC 60079 series for the explosive atmosphere risk assessment, ISO 14121 series for the safety of machinery, etc. However, with reviewing the risk assessment methodologies suggested by those standards, Human and Organizational Factor (HOF) is a less considered (even a neglected) factor in a risk assessment, but can be identified among all phases of a system life cycle.

Meanwhile, the 16 industries' interviews were conducted by all INNHF fellows. As a part of the results, it has also shown that across all sectors use standards to support their risk assessment and safety management. The international standards most used were OHSAS 18001, ISO 9001, ISO 14001, and ISO 31000. No human factors standards were mentioned by any interviewee.

Hence, questions occur: "Are current safety standards and their suggested risk assessment methodologies enough to apply without considering human and organizational factors (HOF)?" "How to analyze the HOF influence on identified hazards", and "how to integrate HOF into current risk assessment methodology?" With these questions, in Chapter 2, an overview of current Risk Assessment Methodologies and Human Factor Integration (HFI) techniques was conducted, in order to try to find a way on the integration of HOF into risk assessment methodologies.

Chapter 2. Literature Review

How to Integrate HOF into Risk Assessment Methodologies?

Outline:

2.1 Current Risk Assessment Methodologies

2.2 Human Factor Integration (HFI)

2.3 Discussion: How to Integrate HOF into Risk Assessment Methodology

Chapter 2. Literature Review

Risk assessment process generally divided into risk identification, risk analysis, and risk evaluation (Figure 2.1).

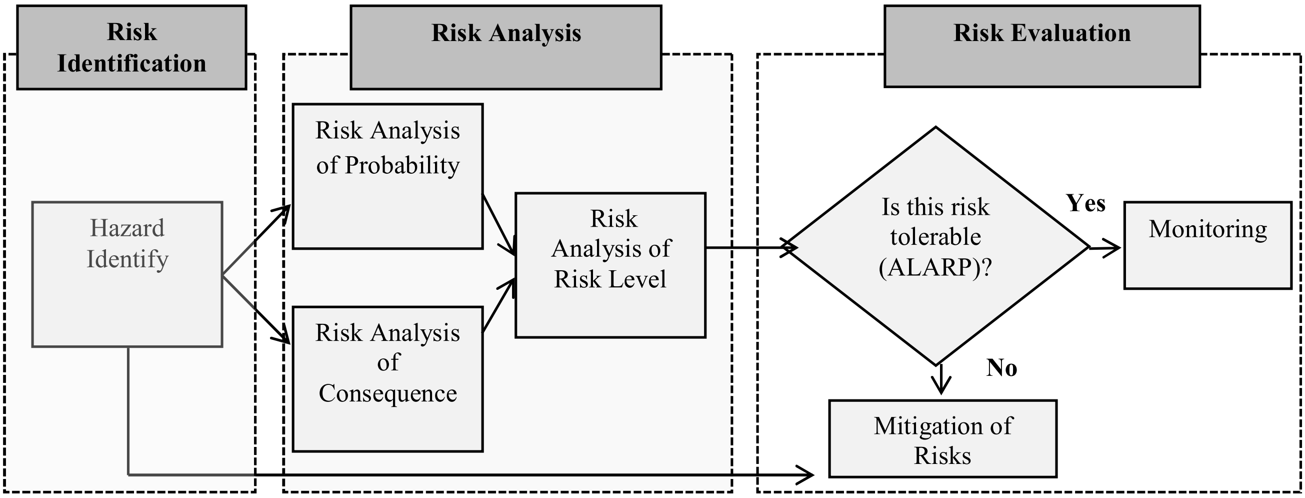


Figure 2.1 Risk Assessment Process

1) Risk Identification

> *"**Risk identification** is the process of finding, recognizing and recording risks, which includes identifying the causes and source of the risk, events, situations" (ISO/IEC 31010: 2009).*

Risk Identification establishes the bases of the risk analysis. The objective is to reveal all possible potential hazards that exist in a system or organization. The whole risk assessment would be affected if the risk identification is not conducted properly. The risk identification phase is normally based on the sources: plan & diagram, process & reactions, products & materials, probability & frequency, policy & management, environment, texts & historical knowledge (Tixier et al., 2002). Many analytical methods have been developed for the use in hazards identification. ISO&IEC 31010 (2009) suggests three groups for the risk identification: a) Evidence based methods, e.g. checklists, reviews of historical data; b) Systematic team approaches where a team of experts follow a systematic process to identify risks;

and c) Inductive reasoning techniques, such as HAZOP. Meanwhile, some techniques like brainstorming and Delphi methodology can also be introduced, in order to improve the accuracy and completeness.

2) Risk Analysis

> *"**Risk analysis** is about developing an understanding of the risk. It provides an input to risk assessment and to decisions about whether risks need to be treated." (ISO/IEC 31010: 2009).*

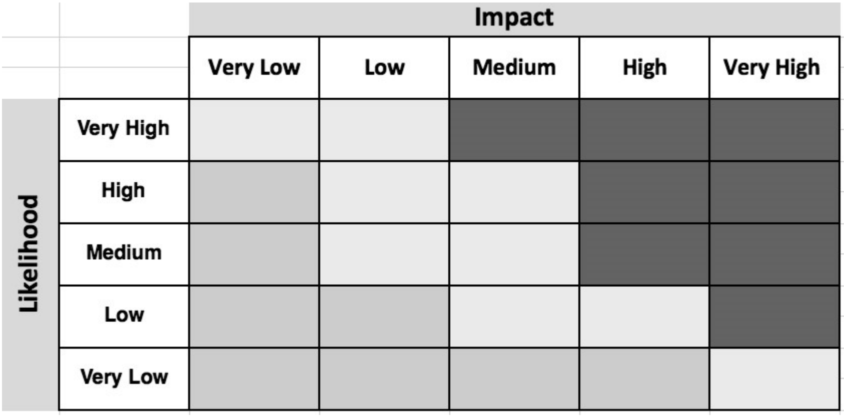
Risk analysis involves consideration of the causes and sources of risk, their consequences and the probability of those consequence occurrence. Most risk analysis techniques can be classified as qualitative and quantitative methods. For each method, deterministic method, probabilistic method or both of them can be applied. In ISO/IEC 31010 (2009) suggests three groups of risk analysis techniques:

- *Qualitative methods* define consequence, probability and the level of risk by significance levels, such as "high, medium, and low".
- *Quantitative methods* estimate practical values for consequences and their probabilities, and produces values of the risk level in specific units.
- *Semi-quantitative methods* use numerical rating scales for consequence and probability and combine them to produce a level of risk using a formula.

3) Risk Evaluation

> *"**Risk evaluation** involves comparing estimated levels of risk with risk criteria defined when the context was established, in order to determine the significance of the level and the type of risk" (ISO/IEC 31010: 2009).*

The purpose of risk evaluation is to assist in making decisions, based on the outcomes of risk analysis, about which risks need to be treated and the priority for the risk control (ISO 31000:2009). In the summary from Tixier et al. (2002), the approaches for the risk evaluation can be grouped as: a) Management Decisions, b) List of Risks, c) Probabilistic Results, and d) Risk Index/Level.



		Impact				
		Very Low	Low	Medium	High	Very High
Likelihood	Very High	░	░	▓	▓	▓
	High	▒	░	░	▓	▓
	Medium	▒	░	░	▓	▓
	Low	▒	▒	░	░	▓
	Very Low	▒	▒	▒	▒	░

Figure 2.2 Example of a Risk Matrix

Among those approaches, the risk index/level is the easily applicable method. A common approach is to divide risks into three bands: upper, middle, and lower band. The "as low as reasonably practicable' or ALARP criteria system used in safety applications follows this approach (ISO/IEC 31010, 2009). ***As Low As Reasonably Practicable (ALARP Principle) And Still Stay In Business (ASSIB Principle)*** (Reason, 2008) were introduced as the two principles for the risk control. It is hardly to achieve both of these two things at the same time, at least, ALARP should be considered during the daily safety management. ALARP principle means keeping your risks "as low as reasonably practicable", and ALARP are also from the abbreviation of the last five words (IEC 61508-5, 1998). It indicates a willingness to live with a risk so as to secure certain benefits, at the same time expecting it to be kept under review and reduced as and when this can be done. Figure 2.3 outlines the regions of ALARP, a) the risk is so great that it must be refused altogether, or b) the risk is, or has been made, so small as to be insignificant, or c) the risk falls between the two states specified in a) and b).

If a risk falls between the two extremes (i.e. the unacceptable region and broadly acceptable region) and the ALARP principle has been applied. Below the tolerability region, the levels of risk are regarded as so insignificant that no need to do further improvements. If above the ALARP level, industries should consider how to reduce the risks in the unacceptable region in the ALARP level with a balance of costs and benefits, in order to keep operations of industries still stay in business (ASSIB).

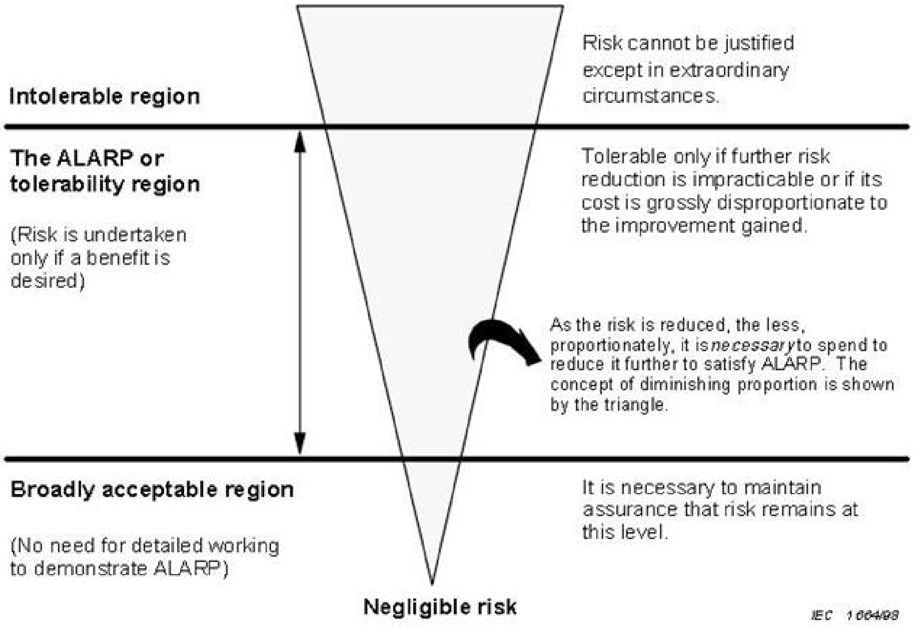


Figure 2.3 Tolerable Risk and ALARP

2.1 Current Risk Assessment Methodologies

ISO/IEC 31010:2009 also described 31 ***risk assessment methodologies***. Most of them are qualitative methods. In addition, Marhavilas, et al. (2011) reviewed the scientific literature from 2000-2009, and summarized 18 risk assessment methodologies in three groups: qualitative techniques, quantitative techniques, and hybrid techniques. It is illustrated for the reviewing period 2000-2009 that 53.71% of the application domain is in industry; 12.87% is in Transportations; 12.38% is in Mechanics; and others. Among the reviewed techniques, 65.63% of the methods are quantitative. In Chapter 2, the review work is mainly based on their contributions, and conducting the review of the common applied risk assessment methodologies in three groups: qualitative, quantitative, and hybrid groups.

2.1.1 Overview of qualitative risk assessment methodology

Table 2.1 Overview of Qualitative Risk Assessment Methodologies

Risk Assessment Methodologies	Description	Major Application Industrial Domain	Risk Assessment Processes Support
1) Brainstorming	It is stimulating and encouraging free-flowing conversation amongst a group of knowledgeable people to identify potential failure modes and associated hazards, risks, criteria for decisions and/or options for treatment (ISO/IEC 31010:2009).	Various Industries	Risk Identification
2) Structured Interviews	Individual interviewees are asked a set of prepared questions to view a situation and identify risks (ISO/IEC 31010:2009).	Various Industries	Risk Identification
3) Scenario Analysis	A method given to the development of descriptive models of how the future might turn out. It cannot predict the probabilities of identified changes but can assist in making decisions and planning future strategies by considering consequences (e.g. best, worst, and expected case) of foreseeable changes (ISO/IEC 31010:2009).	Various Industries	Risk Identification Risk Analysis
4) Checklists	A systematic evaluation consists of lists of hazards, risks or control failures that have been developed usually from experience, previous risk assessment, or historical records of past failures (TECH 482/535 Notes, 2005).	Various Industries	Risk Identification
5) Task Analysis	This process analyse the way that people perform the tasks and subtasks in their work environment in a retrospective mode during the detailed investigation of major incidents. Various methods can be applied to do task analysis, the main dimensions of methods are the action oriented approaches (e.g. HTA) and the cognitive approaches (e.g. CADET) (Embrey, 2000; Marhavilas et al., 2011).	Various Industries	Risk Identification
6) Preliminary Hazard Analysis (PHA)	A simple, inductive, and qualitative method of analysis whose objective is to identify the hazards that can cause harm for a given activity, facility or system. It is most commonly carried out early in the development of a project when there is little information on design details or operating procedures (ISO/IEC 31010:2009).	Various Industries	Risk Identification Risk Analysis Risk Evaluation
7) Hazard Identification Studies (HAZID)	The HAZID process can be based on the client's hazard control hierarchy or based on one provided by consultancy firms. A process that breaks a project down into component parts for detailed analysis. This analysis helps identify hazards that could cause injury to personnel, asset damage or loss, environmental damage, loss of production, or liability/litigation. Hazards require some form of control in order to mitigate risks. Using this tool during early phases of the project may provide key information that determines whether the project is feasible (Siddiqui, et al., 2014).	Various Industries	Risk Identification Risk Evaluation
8) What-if Analysis & SWIFT	SWIFT was originally developed as a simpler alternative to HAZOP. It is a systematic, team-based study, utilizing a set of 'prompt' words or phrases that is used by the facilitator within a workshop to stimulate participants to identify risks (Ayyub, 2003; ISO/IEC 31010:2009).	Chemical and Petrochemical Plant	Risk Identification Risk Analysis Risk Evaluation

Table 2.1 Overview of Qualitative Risk Assessment Methodologies (cont.)

Risk Assessment Methodologies	Description	Major Application Industrial Domain	Risk Assessment Processes Support
9) Sequentially Timed Event Plotting (STEP) Technique	STEP provides a comprehensive framework for accident investigation from the description of the accident process, through the identification of safety problems, to the development of safety recommendations. It is the multi-linear event sequence, and uses universal event building blocks, organized into sequentially timed events matrices with links showing causal relationships among events to describe the processes required to produce outcomes of interest (Herrera & Woltjer, 2009; Marhavilas et al., 2011).	Various Industries	Risk Identification
10) Hazard and Operability Study (HAZOP)	A brainstorming, qualitative, and inductive risk assessment tool, meaning that it is a "bottom-up" risk identification approach, where success relies on the ability of subject matter experts (SMEs) to predict deviations based on past experiences and general subject matter expertise (ISO/IEC 31010:2009).	Chemical Process Industry	Risk Identification Risk Analysis Risk Evaluation
11) Hazard analysis and critical control points (HACCP)	HACCP provides a structure for identifying hazards and putting controls in place at all relevant parts of a process to protect against the hazards and to maintain the quality reliability and safety of a product. HACCP aims to ensure that risks are minimized by controls throughout the process rather than through inspection of the end product. It is developed to ensure food quality (ISO/IEC 31010:2009).	Food Industry	Risk Identification Risk Evaluation
12) Failure modes and effects analysis (FMEA)	An FMEA is a design tool that is commonly defined as "a systematic process for identifying potential design and process failures before they occur, with the intent to eliminate them or minimize the risk associated with them". FMEA procedures are based on standards in the reliability engineering industry, both military and commercial (IEC 60812:2006).	Various Industries	Risk Identification
13) Root Cause Analysis (RCA)	RCA is focused on asset losses due to various types of failures while loss analysis is mainly concerned with financial or economic losses due to external factors or catastrophes. It attempts to identify the root or original causes instead of dealing only with the immediately obvious symptoms (ISO/IEC 31010:2009).	Various Industries	Risk Identification Risk Analysis Risk Evaluation
14) Cause-and-effect analysis	It is a structured method to identify possible causes of an undesirable event or problem. It organizes the possible contributory factors into broad categories so that all possible hypotheses can be considered. The information is organized in either a Fishbone or sometimes a tree diagram (ISO/IEC 31010:2009).	Various Industries	Risk Identification

2.1.2 Overview of quantitative risk assessment methodologies

Table 2.2 Review of Quantitative Risk Assessment Techniques

Risk Assessment Methodologies	Description	Major Application Industrial Domain	Risk Assessment Processes Support
Proportional Risk Assessment Technique (PRAT)	Using the formula to calculate the risk, and each factor ranges 1-10 scale, the quantity R can be expressed in the scale of 1-1000; Based on the quantity R, evaluate the risk. The formula is: $\mathbf{R=P*S*F}$ Where R is Risk; P is the Probability Factor; S is the Severity of Harm Factor; F is the Frequency Factor. (Marhavilas et al., 2011; Reniers et al., 2005).	Various Industries	Risk Analysis Risk Evaluation
Decision Matrix Risk Assessment (DMRA) Technique	Systematic approach for estimating risk, which is consisting of measuring and categorizing risks on an informed judgment of the importance of probability and consequence. Evaluate based on the Decision Matrix and decision-making table. The measurement of risk (R) can be expressed by the relation: $\mathbf{R=S * P}$ where S is the severity and P is the likelihood. (Haimes, 2009; Marhavilas et al., 2011; Marhavilas & Koulouriotis, 2008).	Various Industries	Risk Analysis Risk Evaluation
F-N Curve	Associated with operation of given complex technical system, using F-N curve to measure and evaluate the risk. The F-N curve according to the formula: $$\mathbf{R} = \sum_k \boldsymbol{F_k} * \boldsymbol{N_k}$$ Where R is risk; F_k is the frequency of k-th accident scenario; and N_k is the number of fatalities resulting from k-th scenario. Evaluate whether risk (F-N curve) is inside the area of ALARP (Marhavilas et al., 2011).	Chemical Process Industry	Risk Analysis Risk Evaluation
Quantitative Assessment of Domino Scenarios (QADS)	The severity of accidents where propagation effects took place, generally named as "domino" or "knock-on" accidents, using the quantitative methods to assess a primary accidental scenario, a propagation effect, one or more secondary accidental scenarios, and an escalation of the consequences of the primary event (Cozzani and Zanelli, 2001; Landucci et al, 2012; Marhavilas et al., 2011).	Various Industries	Risk Analysis

Table 2.2 Review of Quantitative Risk Assessment Techniques (cont.)

Risk Assessment Methodologies	**Description**	**Major Application Industrial Domain**	**Risk Assessment Processes Support**
Predictive, Epistemic Approach (PEA)	PEA approach provides formal means for combining hard data and subjective information and allows predicting observable quantities, like occurrence, or not, of an accidental event, or the number of fatalities or the magnitude of financial loss in a period of time in the form of mathematical models. In view of forecasting accidental actions (AAs), PEA should define as a way of interpreting and specifying the frequency Fr(AA) and p.d. P (m|AA); The final result of forecasting an AA can be expressed by an action model $\mathbf{Fr(x)=Fr(AA)(1-F_X(x\mid\pi_x))}$ Where, p.d. is the probability distributions; x is the vector of AA characteristics; X is the random vector with a distribution function (d.f.), which models an epistemic uncertainty in x; Fr(AA) is the frequency expressing the epistemic uncertainty related to a future occurrence of AA; p.d. $F_X(x\mid\pi_x)$ expresses epistemic uncertainty in the event X. (Apeland et al., 2001; Marhavilas et al., 2011).	Various Industries	Risk Analysis
The Weighted Risk Analysis (WRA)	WRA is an overall mathematical-economic decision problem for balancing safety measures for all kinds of aspects by expressing both positive/negative risks and benefits of a project. It is a tool using weighing factors for all risks, in order to make them comparable to each other in one-dimension (Marhavilas et al., 2011). Weighted risk analysis of different decision-making elements can be expressed as: $R_w = \sum_{j=1} a_j \sum_{i=1} R_{ij}$ Where safety measures can be balanced as: $C(tot) = C_0(y) \sum_{i=0} \frac{R_{wj}}{(1+r)^j}$ C_{tot} is the total costs; C_0 is the investment in a safety measure; y is the decision parameter; j is the number of the year; r is the real rate of interest.	Various Industries	Risk Analysis

2.1.3 Overview of hybrid risk assessment methodologies

Table 2.3 Review of Hybrid Risk Assessment Techniques

Risk Assessment Methodologies	Description	Major Application Industrial Domain	Risk Assessment Processes Support
Event Tree Analysis (ETA)	Event tree analysis (ETA) is an analysis technique for identifying and quantifying the sequence of events in a potential accident scenario following the occurrence of an initiating event. ETA utilizes a visual logic tree structure known as an event tree (ET) (Ericson, 2005; Marhavilas et al., 2011).	Various Industry	Risk Analysis
Fault Tree Analysis (FTA)	Fault tree analysis (FTA) is an analysis technique that visually models how logical relationships between equipment failures, human errors, and external events can combine to cause specific accidents. It is a technique for identifying and analysing factors that can contribute to a specified undesired event (called the "top event"). (Marhavilas et al., 2011; Vesely et al., 1981; IEC 61025, 2006).	Various Industry	Risk Analysis
Bow Tie Analysis	Bow tie analysis is a simple diagrammatic way of describing and analysing the pathways of a risk from causes to consequences. It can be considered to be a combination of the thinking of a fault tree analysing the cause of an event and an event tree analysing the consequences (ISO/IEC 31010:2009).	Various Industry	Risk Analysis
Integrated Dynamic Decision Analysis (IDDA)	The IDDA method provides a full representation of the plant states during operations (ordinary, incidental or irregular operating conditions), as well as all the possible occurrences patterns (description of events), expressed in a set of mutually self-excluding sequences. Availability of the full set of alternative allows the complete spectrum of possible probability-consequence conditions to be used as a basis for decisions in risk reduction and control (Demichela & Piccinini, 2004).	Various Industry	Risk Analysis

2.2 Human Factor Integration (HFI)

With the growing in complexity, increased automation and functional sophistication of high-technology systems, apart from some events caused by an unusual or unforeseeable manifestation (such as an earthquake), in the majority of cases, human became the main or sometimes even the only cause (Hollnagel, 1998). There are still various considerations of "human". An engineer may concern "human" as a system component with the consequence of success or failure of doing specific tasks (Swain & Guttmann, 1983). Psychologists may think human behaviour is essential for the causes of system failure. The more general used model is the socio-technical system. The main errors for human-machine interaction system are caused by the functional failure, human failure, and interaction between them (Figure 2.4, Marhavilas, et al., 2011). The management or the organizational structure (the organizational factor) is also considered as mediating variable that has potential influence on the failure of system.

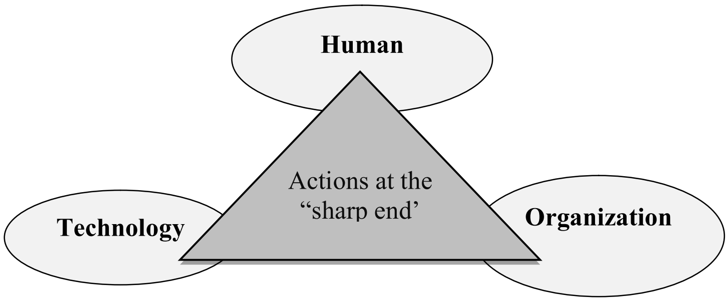


Figure 2.4 The relation between person-related, technology-related, and organization-related factors (Hollnagel, 1998)

Human factors is concerned with understanding the causes of human failures and preventing human failures, which is also an important part of managing "major accident safety'. In UK Ministry of Defence Report (2013), **Human Factors Integration (HFI)** was defined as "HFI is a systematic process for identifying, tracking and resolving People-Related considerations ensuring a balanced development of both technologies and human aspects of capability". The report also mentioned that the HFI process covers six domains: Manpower, Personnel, Training, Human Factors Engineering, System Safety, and Health Hazards. The HFI process is intended to be seen as an activity that supports attention towards all six domains during the entire system design lifecycle.

Stanton et al. (2005) conducted literature review that any method discovered was recorded and added to the database. The result of this initial literature review was a database of over 200 HF methods and techniques, including the following categories of technique:

Table 2.4 HF Technique Categories Summarized by Stanton et al. (2005)

Method category	Description
1) Data collection techniques	Data collection techniques are used to collect specific data regarding a system or scenario. According to Stanton (2003) the starting point for designing future systems is a description of a current or analogous system.
2) Task analysis techniques	Task analysis techniques are used to represent human performance in a particular task or scenario under analysis. Task analysis techniques break down tasks or scenarios into the required individual task steps, in terms of the required human-machine and human-human interactions.
3) Cognitive task analysis techniques	Cognitive task analysis (CTA) techniques are used to describe and represent the unobservable cognitive aspects of task performance. CTA is used to describe the mental processes used by system operators in completing a task or set of tasks.
4) Charting techniques	Charting techniques are used to depict graphically a task or process using standardised symbols. The output of charting techniques can be used to understand the different task steps involved with a particular scenario, and also to highlight when each task step should occur and which technological aspect of the system interface is required.
5) HEI/HRA techniques	HRA techniques are used to predict any potential human operator error that may occur during a man-machine interaction. HRA techniques are used to quantify the probability of error occurrence.
6) Situation awareness assessment techniques	Situation Awareness (SA) refers to an operator’s knowledge and understanding of the situation that he or she is placed in. According to Endsley (1995a), SA involves a perception of appropriate goals, comprehending their meaning in relation to the task and projecting their future status. SA assessment techniques are used to determine a measurer of operator SA in complex, dynamic systems.
7) Mental workload assessment techniques	Mental workload (MWL) represents the proportion of operator resources demanded by a task or set of tasks. A number of MWL assessment technqieus exist, which allow the HF practitioner to evaluate the MWL associated with a task or set of tasks.
8) Team performance analysis techniques	Team performance analysis techniques are used to describe, analyse and represent team performance in a particular task or scenario. Various facets of team performance can be evaluated, including communication, decision-making, awareness, workload and co-ordination.
9) Interface analysis techniques	Interface analysis techniques are used to assess the interface of a product or systems in terms of usability, error, user-satisfaction and layout.
10) Design techniques	Design techniques represent techniques that are typically used during the early design lifecycle by design teams, including techniques such as focus groups and scenario-based design.
11) Performance time prediction techniques	Performance time prediction techniques are used to predict the execution times associated with a task or scenario under analysis.

Human error is a complex construct that has received considerable attention from the HF community. Human error is formally defined as “All those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency’ (Reason, 1990) Human Error Identification (HEI) or Human Reliability Analysis (HRA) techniques are used to identify potential errors that may arise as a result of man-machine interactions in complex systems. HEI/HRA methods can be used either during the design process, or to evaluate error potential in existing systems (Stanton, et al., 2005).

Considering even a simple interactive system, this requires an examination of the links between every possible cause and every possible consequence, it is impossible in practice to make a deterministic analysis. The common solution is to conduct a probabilistic analysis for instead (Hollnagel, 1998). Human Reliability Analysis (HRA) techniques, as one of the important categories in the human factor techniques, aim to identify and quantify human error. Evans (1976) explained that human reliability is a probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system. Human reliability analysis (HRA) is a method that human reliability is estimated, such as HEART, CREAM, NARA, THERP, SPAR-H, etc. (HSL, 2009; Nespoli and Ditali, 2010). Hollnagel (1998) considered HRA techniques with two categories: 1) *Task-dominant approaches* that concerns human doing a task as the consequence of success and failure; and 2) *Cognition-dominant approaches* concerns human cognitions as causes of the human failure.

2.2.1 Overview of task-dominant Human Reliability Analysis (HRA) techniques

Table 2.5 Overview of task-dominant Human Reliability Analysis (HRA) Techniques

HRA Techniques	Description	Major Application Industrial Domain	Potential to Apply within Risk Assessment Processes
1) Task Analysis	Task Analysis is a process of representing a human task in graphical or textual form to assist in the process of Human Factors analysis (Stanton et al., 2005). There are literally hundreds of different methodologies for Task Analysis ranging from textual depictions of the tasks to the popular graphical methods which are the commonly used within industry. Using Flow Charts to model a process is the most common method of Business Process Modelling.	Various Industry	Risk Identification
2) Human Hazard and operability analysis (Human HAZOP)	HAZOP is a technique that uses a committee (4-6 people) of experienced personnel to identify problems with the design or operational intent of a system. It involves a structured consideration of the engineering plans and procedures line by line and uses a keyword approach to identify problems that could occur within the system. “Human HAZOP” which is an application of the approach to focusing on human factors and human/error issues (Whalley, 1988).	Various Industry	Risk Identification Risk Analysis Risk Evaluation

Table 2.5 Overview of task-dominant Human Reliability Analysis (HRA) Techniques (cont.)

HRA Techniques	**Description**	**Major Application Industrial Domain**	**Potential to Apply within Risk Assessment Processes**
3) Technique for Human Error Rate Prediction (THERP)	THERP assumes that human errors for each task can be broken down into omission errors and commission errors. It uses enhanced PSA event trees and that it extends the traditional description of error modes beyond the binary categorization of success-failure. THERP focus the only one dominant factor to Human Error Probability (HEP); the nominal HEP is determined once the task is known and can be modified by other factors (PSFs) later (Swain & Guttmann, 1983; Zhiqiang et al., 2009).	Nuclear Industry	Risk Analysis
4) Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H)	It does not provide specific guidance on how to perform human error identification, but does tell the analyst to decompose each task to either a diagnosis or an action subtask. The analyst determines the system activity type and then provides HEPs for the four combinations of the error type and system activity type. The HEP is adjusted based on eight basic PSFs and the dependency. It has a large U.S. experience base (Gertman et al., 2005; Chandler et al., 2006).	Nuclear Industry	Risk Analysis
5) Nuclear Action Reliability Assessment (NARA)	It is a data-based HRA technique and is a refinement of the HEART technique. NARA does not provide guidance on how to perform human error identification. Instead, the analyst must best match the task being analyzed to one of 14 generic tasks. It provides basic HEP values that apply to these generic tasks. Although NARA has not been applied to any specific domains, it is an enhancement of HEART (modifying the grouping of generic tasks and weighting of PSFs) and, most importantly, it uses the CORE-DATA human error data base (Chandler et al., 2006).	Nuclear Industry	Risk Analysis
6) Workplace Analysis	It is an assessment of your operations, procedures, processes, physical environment and individual workstations. It is a step-by-step, common-sense look at the workplace to find existing or potential hazards for a workplace. Normally, it includes three steps: a) reviewing previous injury records analysis and tracking; b) workplace security analysis, like using a checklist as a tool for walk through; c) walk through the worksite (SFM, 2010).	Various Industry	Risk Identification
7) Workload Assessment	One of the representatives is Subjective Workload Assessment Technique (SWAT). It is developed through the application of a scaling procedure known as conjoint scaling and event scoring. The Scale Development is used to train the subjects on the use of the descriptors and to obtain data concerning how these dimensions combine to create each individual's personal impression of workload. The Event Scoring phase is the experiment where the investigator is interested in obtaining information about the workload associated with task performance (Potter & Bressler, 1989).	Various Industry	Risk Analysis

2.2.2 Overview of cognition-dominant Human Reliability Analysis (HRA) techniques

Table 2.6 Overview of cognition-dominant Human Reliability Analysis (HRA) techniques

HRA Techniques	Description	Major Application Industrial Domain	Potential to Apply within Risk Assessment Processes
1) Cognitive Reliability and Error Analysis Method (CREAM)	CREAM is a context-dominant type HRA technique, and has been developed from the principled analysis of existing approaches and therefore contains a method, a classification scheme, and a model. CREAM has not been developed from the underlying model of cognition, but simply uses it as a convenient way to organize some of the categories that describe possible causes and effects in human actions (Hollnagel, 1998; Zhiqiang et al., 2009).	Various Industry	Risk Identification Risk Analysis Risk Evaluation
2) The Human Factors Analysis and Classification System (HFACS)	The HFACS system is a human error framework that was developed by the US military. It is based on the Reason "Swiss Cheese" model wherein incidents are identified as multiple failures in the safety barriers overlapping and leading to an incident, HFACS is an investigation tool to assist in investigative processes and to target training and preventative measures. The framework describes human error at each of the "four levels of failure" ranging from the unsafe acts of the operators, the preconditions for unsafe acts, unsafe supervision and organisational influences (Shappell & Wiegmann, 2000).	Aviation & Transportation	Risk Identification
3) Human Error Assessment and Reduction Technique (HEART)	It is a general method that is applicable to any situation or industry where human reliability is important. There are 9 Generic Task Types (GTTs) described in HEART, each with an associated nominal human error potential (HEP), and 38 Error Producing Conditions (EPCs) that may affect task reliability, each with a maximum amount by which the nominal HEP can be multiplied (Williams, 1985; Bell & Holroyd, 2009).	Various Industry	Risk Analysis
4) A Technique for Human Event Analysis (ATHEANA)	The premise of the method is that significant human errors occur as a result of "error-forcing contexts" (EFCs), defined as combinations of plant conditions and other influences that make an operator error. It provides structured search schemes for finding EFCs, by using and integrating knowledge and experience in engineering, probabilistic risk assessment (PRA), human factors, and psychology with specific information and insights from the analysis of accidents (Bell & Holroyd, 2009).	Nuclear Industry	Risk Analysis
5) Maintenance Error Decision Aid (MEDA)	MEDA is intended as an incident investigation tool and not as a traditional HRA technology (Rankin, et al., 2000) it does provide a taxonomy that could be useful for a new HRA approach as the MEDA taxonomy focuses on the organizational and design context outside of the error task, probing the environmental, documentation , intrapersonal, cultural and other factors that can influence an error within the environment.	Various Industry	Risk Identification

2.3 Discussion: How to Integrate HOF into the Risk Assessment Methodology?

According to the reviewed risk assessment methodologies, qualitative approaches are easier to apply. Those qualitative approaches normally do not require a lot of time, more specific data resources, and most of these are cheap to use. However, the limitation is contributing the subjective results; and the high education level of experts are expected. Quantitative approaches can provide mathematical risk evaluation, most of them are time-consuming and more expensive to apply. Hybrid techniques combine advantages both of qualitative and quantitative approaches and are more reliable applied in the real workplace. The disadvantages of these hybrid approaches are mostly time consuming and more complicated to use. Thus, different risk assessment methodologies are suggested to apply in terms of various situations.

In addition, given to the reviewed work from Tixier et al. (2002), those reviewed risk assessment methodologies have shown the limitations that should be considered as well: a) The more general the methodology is, the less specificities that can take into account. On the other hand, the more specific the methodology is, the less transposable to another case. b) Knowledge of people whom are conducting the risk assessment is quite important. c) The complexity of some methods requires specific training for their implementation. d) There is a great disconnection between risk assessment methodologies and human factors.

2.3.1 HOF in the risk identification phase

Risk Identification is the process of finding, recognizing and recording risks, which establishes the bases of the risk analysis (ISO/IEC 31010:2009). The objective is to reveal all possible potential hazards that exist in a system or organization. The whole risk assessment would be affected if the risk identification is not conducted properly. From general sources (Tixier et al., 2002) support for the risk identification, potential HOF influences can be found with those sources (Table 2.7):

a) Plan & diagram: site, installations, units, fluid or gas networks, functioning, safety barriers, storage;

b) Process & reactions: operations description, tasks description, reactions and physical and chemical features, process characteristics, kinetics and calorimetrical parameters, normal functioning conditions, operating conditions;

c) Products: products types, physical and chemical properties, quantities, toxicological data;

d) Probability & frequency: failure type, failure probability, initiation and failure frequencies, human failure, failure rate, exposure probability;

e) Policy & management: maintenance, organization, safety policy, SMS, transport management, equipment cost;

f) Environment: site environment, topographical data, population density;

g) Texts & historical knowledge: standards, regulations and documents, historical knowledge.

Table 2.7 Potential HOF Influences among Risk Identification Sources

Risk Identification Sources	HOF Presence & Potential Influences
1) Plan & diagram	HOF can be present as one type of **safety barriers**.
2) Process & reactions	HOF can be described in **the operation descriptions, tasks description, process characteristics, and operation conditions**.
3) Products	--
4) Probability & frequency	HOF has potential to fail (e.g. **human error probability**).
5) Policy & management	HOF plays an important role in **policy and management** part.
6) Environment	--
7) Texts & historical knowledge	HOF are mentioned in **standards, regulations, historical knowledge**.

2.3.2 HOF in the risk analysis phase

Risk analysis is dealing with the probability and consequence analysis, and then to determine the relevant risk level. The general approaches are conducting the qualitative, quantitative, or semi-quantitative analysis.

1. Qualitative methods	2. Quantitative methods
1a. Deterministic,	2a. Deterministic,
1b. Probabilistic, or	2b. Probabilistic, or
1c. Both	2c. Both

Since the HOF identified in the process of the risk identification also has potential probability to fail, relevant human factors integration (HFI) techniques (e.g. Human Relibality Analysis, HRA) can be applied for the probability and consequence analysis, in order to support the risk level determination.

2.3.3 HOF in the risk evaluation phase

The risk evaluation of the HOF influence can be taken into account as either an independent part or an integrated solution. Figure 2.5 shows the interaction of the HOF and the system functions. Human errors from operational activities, maintenance activities, and insufficient management could contribute to functional failures. The HOF influence here is considered as an integrated part within the final risk evaluation.

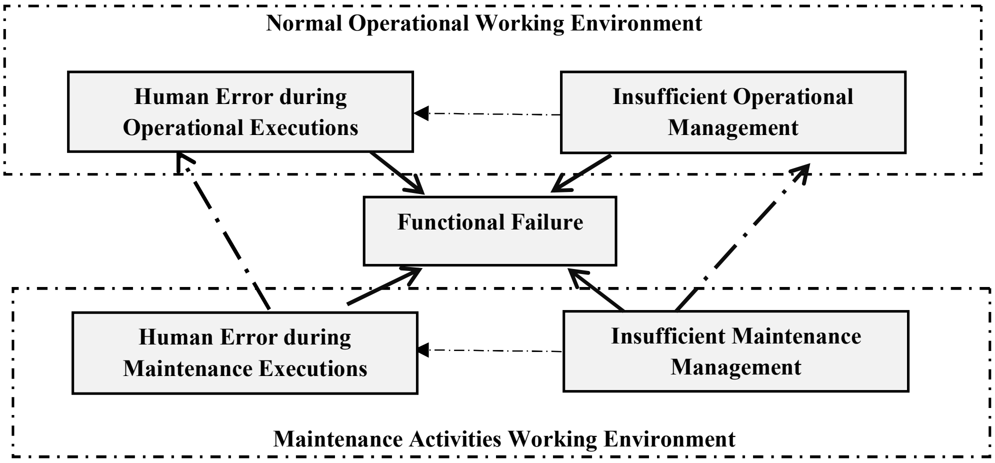


Figure 2.5 HOF influence on a functional failure among normal operations and maintenance activities

Chapter 3. Specific Application Domain: the ATEX Risk Assessment

Main Characteristics of Traditional ATEX Risk Assessment Methodologies

Chapter Objectives:

3.1 Methodology Review 1: Probabilistic ATEX Risk Assessment (ATEX-PRA)

3.2 Methodology Review 2: FUZZY ExLOPA

3.3 Methodology Review 3: DSEAR Methodology

3.4 Methodology Review 4: RASE ATEX Risk Assessment

3.5 Methodology Review 5: Cavaliere's Manual

3.6 Discussion: Main Characteristics of Traditional ATEX Risk Assessment Methodologies

Chapter 3. Risk Assessment in a Specific Application Domain: the ATEX Risk Assessment

Start from July 2003, EU organizations must follow the directives to protect employees away from explosion risks under potential explosive atmosphere environment.

An explosive atmosphere is “a mixture of flammable substances with air, in the form of gas, vapour, dust or fibres under atmospheric conditions, which, after ignition, permits self-sustaining propagation” (CEI EN 60079-10-1, 2010). This potential hazard associated with explosive atmosphere is released by an effective ignition source (EN 1127-1, 2007). As a safety principle, “equipment in which flammable materials are handled or stored should be designed, operated and maintained, in order to guarantee any releases of flammable material that are kept to a minimum level, with regard to frequency, duration and quantity” (IEC 60079-10-1, 2008). ATEX (explosive atmosphere) risk assessment is required when any equipment or protective systems are intended for use in potentially explosive atmospheres. Some ATEX risk assessment methodologies were proposed:

3.1 Methodology Review 1: Probabilistic ATEX Risk Assessment (ATEX-PRA)

Lisi and Milazzo (2010) described a quantitative methodology of the explosive atmospheres (ATEX) risk assessment. This procedure requires a detailed knowledge of the system (workplace and activities).

3.1.1 Step 1: Area classification

The area classification aims to identify the presence of zones characterized by the explosion hazard. The standard EN 60079-10 (2010) is needed, and other guidelines are used for the specific requirements from countries. Like in Italy, Guide CEI 31-35 (2012) and Guide CEI 31-56 (2007) are applied depending on the type of emission sources, such as gas, liquid or dust. These standards or guidelines provide the probability of explosive atmospheres (Table 3.1), which can be used for the probabilistic risk assessment.

Table 3.1 Probability and Duration of Explosive Atmospheres

Area Classification Zone	Probability of Explosive Atmosphere Formation in 365 days	Duration, t (hour/year)
Zone 0/20	$P>10^{-1}$	t > 1000 h
Zone 1/21	$10^{-1}>P>10^{-3}$	10 h < t < 1000 h
Zone 2/22	$10^{-3}\geq P>10^{-5}$	0.1 h < t < 10 h

3.1.2 Step 2: Probability of ignition source presence

In order to obtain the probability of ignition source, first is to identification of ignition source where UNI EN 1127-1 (2001) provides a list of 13 main ignition sources to support (Table 3.2).

Table 3.2 Possible ignition sources according to EN 1127-1 (2011)

- Hot surfaces	- Electromagnetic waves
- Flames, hot gases	- Ionizing radiations
- Mechanical sparks	- High-frequency radiation
- Sparks from electrical equipment	- Ultrasounds
- Static electricity	- Adiabatic compression
- Catholic protection and corrosion protection	- Chemical reactions
- Lightning	

In order to handle with the quantification analysis of identified ignition sources, methods such as historical analysis, fault tree analysis, FMEA or FMECA, or specific analytic procedures could be applied to assess the probability or the likely effectiveness of each identified ignition source.

3.1.3 Step 3: Consequences analysis

The explosion consequences must be estimated for each identified emission source. The targets are the *estimation of the overpressure* and *the distance from the source*. Many simplified models are available in Lees (1996) and in the Yellow Book 1997, such as the equivalent TNT model and the equivalent piston model which allow the quantification of the distance where a pressure wave reaches the value of 0.03 bar.

3.1.4 Step 4: Presence of workers

The presence of personnel in workplace depends on the number of workers in the potential zones and on their probable presence. The number of workers involved in a potential explosion can be calculated by using the damage zones, and the probability of presence can be calculated by analysing the worker activities. The presence of workers p_w (probability) is calculated by Eq. (3.1):

$$p_w = (\frac{A_i}{A_{est}})p_i \quad \text{Eq. (3.1)}$$

where,

- A_i is impact zone of the explosion;
- A_{est} is the whole area of the establishment;
- p_i is the probability of the presence of personal in the establishment.

3.1.5 Step 5: ATEX Risk evaluation

Finally, Eq. (3.2) is proposed for the calculation of the risk, R_{ae} (ATEX Risk):

$$R_{ae} = p_e \times p_a \times p_w \quad \text{Eq. (3.2)}$$

where,

- p_e is the probability of release of an inflammable substance from an emission source;
- p_a is the probability of the presence of an ignition source;
- p_w is the presence of workers in the impact area (probability).

As the major risk and smaller impact area can be studied in the same way, the authors provide the uniform approaches of risk evaluation, which is the ALARP acceptability criteria.

$R_{ae} < 10^{-6}$	Risk is acceptable;
$10^{-6} < R_{ae} < 10^{-4}$	Risk must be reduced as low as technically and economically possible;
$R_{ae} > 10^{-4}$	Risk is not acceptable.

3.2 Methodology Review 2: FUZZY ExLOPA

In order to determine explosion risk, the methodology called ExLOPA was proposed (Markowski, 2007). The ExLOPA is based on the original work of CCPS (2001) for LOPA but takes into account some typical factors:

1) the frequency of an explosive atmosphere occurrence,
2) the probability of the presence of the effective ignition sources, and
3) the probability of failure for appropriate explosion prevention and mitigation measures.

However, the lack of detailed data on failure rates of the safety prevention and mitigation means, uncertainties in available data on probability of ignition sources as well as other imprecision a vagueness connected with the consequence analysis, may cause the uncertainty in results. The Fuzzy Logic can be assistant because it deals with uncertainty and imprecision.

Figure 3.1 shows the Structure of ExLOPA. R_n, defined as “the possibility of an explosion with unwanted consequences”, is expressed as in Eq. (3.3):

$$R_n\,(T_{EXP})=f\,(F_{atex},\, P_{EFI},\, F_{SM},\, SC) \qquad \text{Eq. (3.3)}$$

where,

- F_{atex} is the frequency of the occurrence of an explosive mixture;
- P_{EFI} is the probability of the presence of an effective ignition source;
- F_{SM} is the probability of failure of safety measures;
- SC is the severity of consequence of the explosion;
- T_{exp} is the time of exposure (work time).

ExLOPA expresses all these variables in the form of qualitative categories. The relations between them are provided by “IF-THEN” inference engine rules. The exposure time is used to help for determining the final risk level via the risk matrix.

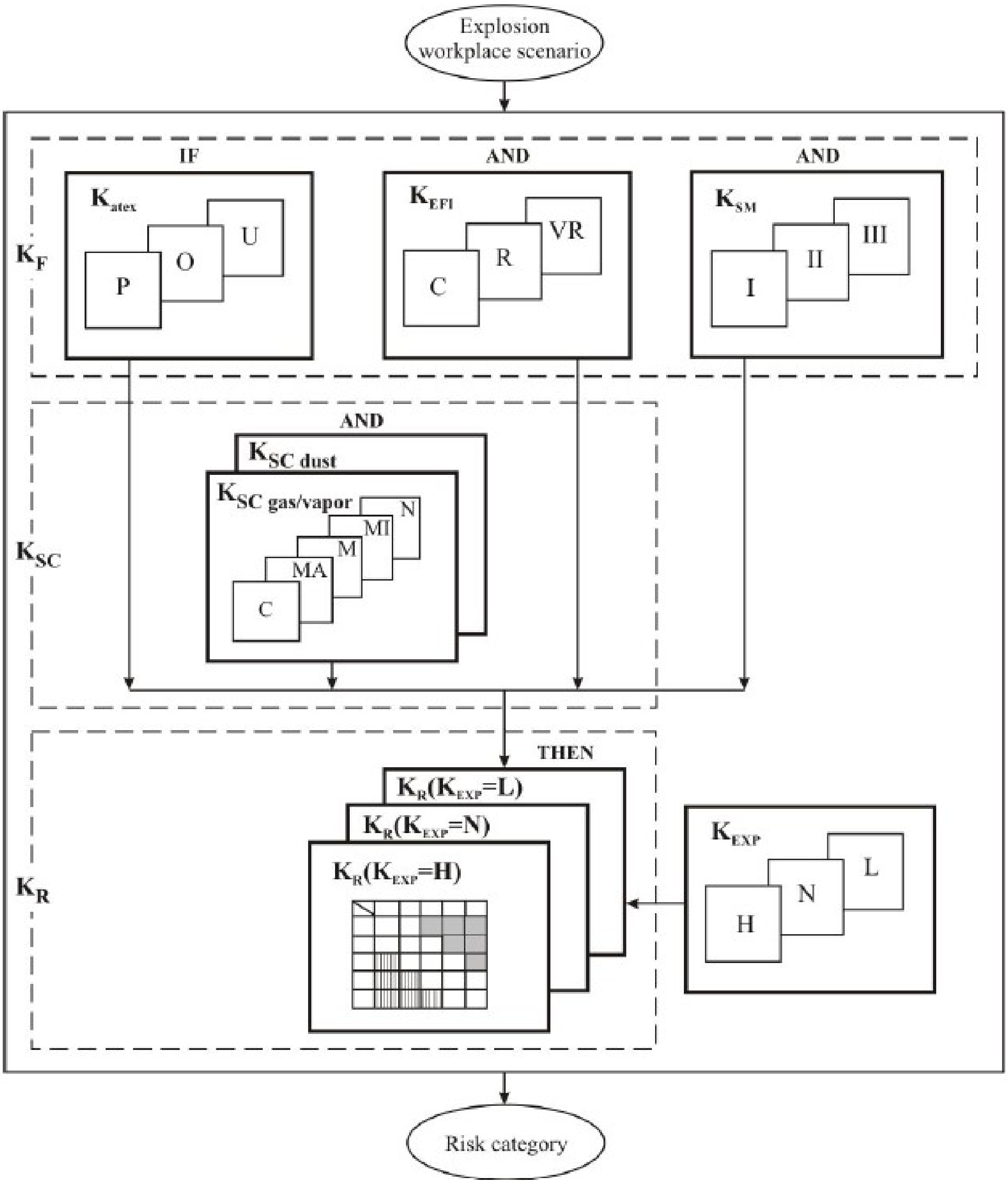


Figure 3.1 The Structure of ExLOPA (Markowski, et al., 2011)

3.2.1 Step 1: Estimation of the frequency of mitigated explosion, K_F

Estimation of the frequency of mitigated explosion (K_F) relies on three factors:

- Frequency of an explosive mixture occurrence, F_{atex};

- Probability of an effective ignition source, P_{EFI};
- Probability of safety measures failure, F_{SM}.

The frequency of an explosive mixture occurrence is given by the classification of hazardous area according to the standard EN 60079-10-1 (2010). The frequency category is provided in Table 3.3.

Table 3.3 Frequency category of atmospheric explosive mixture occurrence, K_{atex}

Classification of hazardous area		Description		Persistence time (h/year)	Frequency rate per year	Linguistic frequency category, K_{atex}
Gas/Vapour	**Dust**					
0	20	Will persist permanently or for a long period or frequently	In normal operation	>1000	~1	P
1	21	Likely to occur in normal operation (Occasionally)	Also in the case of foreseeable faults	>10	~10^{-2}	O
2	22	Unlikely (not expected in normal operation)	Even in the case of rarely occurring faults	<10	~10^{-3}	U

The standard EN1127-1 (2007) distinguishes thirteen types of ignition sources. Checklist can be applied with questions to identify: 1) the presence of ignition sources; 2) effectiveness according to MIE (minimum ignition energy); 3) the frequency of the identified ignition source occurrence. The probability category is provided in Table 3.4.

Table 3.4 Probability category of effective ignition source, K_{EFI}

Category	Description	Range of ignition probability	Probability used in ExLOPA	Linguistic probability category, K_{EFI}
Continuous (Certain)	Operational type, e.g. electrostatic charges when pouring, mixing, pumping, filtering or open flames from burner	Up to 1	~1	CO
Rare	Due to occasional failure of control ignition parameters. E.g. hot surface from damaged surface of a boiler	0.1-0.01	~10^{-2}	R
Very Rare	Due to very rare failure of control ignition parameters. E.g. failure of intrinsically safe electrical equipment. (Ex) or radio frequency sources	0.01-0.001	~10^{-3}	VR

The types of safety layers for atmospheric explosion are provided by the standard EN 1127-1 (2007), which includes two main types: prevention layer (B1, B2, B3) and protection layer (B4, B5). The calculation used follows the requirements for the equipment and protective systems intended for use in potentially explosive atmospheres (ATEX 100).

Table 3.5 Probability category of safety measure, K_{SM}

Category	Description	Range of failure probability	Probability of failure on demand PFD	Linguistic probability category, K_{SM}
Very high	Basic requirements for control of ignition source plus possibly two additional independent explosion protection measures	0.01-0.001	$\sim10^{-3}$	I
High	Basic requirements plus possibly one additional independent explosion protection measure	0.1-0.01	$\sim10^{-2}$	II
Standard	Basic requirements for ignition source	Up to 1	$\sim10^{-1}$	III

Given to the probability or frequency of each factor, the qualitative categories were identified. Hence, K_F is estimated via the Fuzzy 'IF-THEN' rules.

3.2.2 Step 2: Estimation of the severity of the explosion consequences, Ksc

The severity of an explosion is described by the damages (or consequences) occurring due to the impact of the explosion scenario. It is a complex task which is usually given to consequence models. ExLOPA takes into account the estimation of the severity of consequences using matrix based on the level of human harm for each particular explosion scenario (Table 3.6).

Table 3.6 Severity of consequences category, K_{SC}

Category	Description	Explosive mass category (kg)		Linguistic severity category, K_{SC}
		Gas/Vapour	Dust	
Negligible	Very minor or no injury with no lost time	0-1	0-5	N
Minor	Minor injury, no lost time	>1-5	>5-10	MI
Medium	Single injury with short lost time (reversible effects)	>5-10	>10-50	M
Major	Serious injuries – irreversible effects	>10-50	>50-100	MA
Catastrophic	Fatality or multiple serious injuries	>50	>100	C

3.2.3 Step 3: Estimation and assessment of the explosion risk, K_R

The estimation of the explosion risk (K_R) relies on the K_F, K_{SC}, and K_{EXP}. K_F and K_{SC} are obtained via step 1 and step 2. K_{EXP} is the time of exposure which reflects the presence of workers in the hazardous zone. Three frequency categories are wstablished: High (H) representing almost continuous exposure; Noticeable (N) for occasional exposure; and Low (L) for rare exposure (Table 3.7).

Table 3.7 Matrix for category of time of exposure

		Frequency of exposure			
		Every day	Every week	Every month	Every year
Duration of exposure	Below 1 hour	N	L	L	L
	1 to 4 hours	H	N	N	L
	Above 4 hours	H	H	N	N

The risk assessment is based on the matrix:

Table 3.8 Explosion risk matrix

		Severity of consequences, K_{SC}				
		N-Negligible	MI-Minor	M-Medium	MA-Major	C-Catastrophic
Explosion Frequency, K_F	A-very often	TA	TNA	NA	NA	NA
	B-often	TA	TA	TNA	NA	NA
	C-moderate	A	TA	TA	TNA	TNA
	D-seldom	A	A	TA	TA	TNA
	E-very seldom	A	A	A	TA	TA

According to Figure 3.1 (the structure of ExLOPA) and factors mentioned above, the input and output fuzzy sets of each factor are in terms of linguistic categories. Fuzzy logic rules can be expressed as:

- For evaluation of K_F: “IF K_{atex} (category) and K_{EFI} (category) and K_{SM} (category) THEN K_F”
- For evaluation of K_R: “IF K_F (category) and K_{SC} (category) THEN K_R”.

3.3 Methodology Review 3: DSEAR Methodology

DSEAR (The Dangerous Substances and Explosive Atmospheres Regulations of 2002) is the United Kingdom's implementation of the European Union-wide ATEX directive. DSEAR are concerned with protection against risks from fire, explosion and similar events arising from dangerous substances and potentially explosive atmospheres. According to the regulations, BCGA (British Compressed Gases Association, 2008) proposed a methodology:

3.3.1 Step 1: Area classification

The area classification refers to BS EN 60079. It includes: 1) emission source identification; 2) likelihood of release; 3) operation condition (pressure and temperature); 4) ventilation conditions; hence, in order to determine the type of zone (both internal and external).

The likelihood of release is divided into four levels (3,2,1,0), which are later used in a calculation in the risk assessment matrix:

3- continuous (permanent or long periods of release to atmosphere during normal operation);
2- primary (release expected during normal operation);
1- secondary (release NOT expected during normal operation);
0- probability considered negligible, DSEAR risk assessment not required.

3.3.2 Step 2: Ignition source and personnel exposure

Four categories of ignition source are mainly concerned: 1) Heat Energy, 2) Mechanical Energy, 3) Chemical Energy, and 4) Electrical Energy. Meanwhile, the personnel exposed to these dependent upon the activity taking place.

The likelihood of ignition source occurring are performed. As a result, one of four levels is assessed:

3- Present continuously or for long periods (>1000 hours/year)
2- Likely to occur (>10 <1000 hours/year)
1- Not likely to occur or infrequent and for short periods (<10 hours/year)
0- Not present

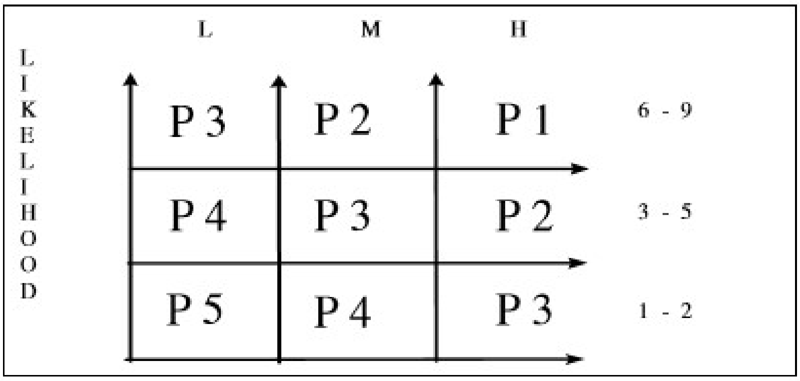
3.3.3 Step 3: Risk assessment

The risk assessment is given to probability, consequence and existing control measures utilising a ranking matrix. Three risk assessments (for normal operation, filling operations, and maintenance operations) are conducted because of the different particular operations.

The likelihood of explosion/fire is by multiplying the likelihood of a flammable atmosphere (taken from Step 1) and the likelihood of having an ignition source occurring (taken from Step 2). The value is up to a maximum of 9. The consequence & severity of explosion/fire refers to:

H=Major impact or major injury/fatality;
M=Serious impact or lost time injury;
L=Minor impact or first aid case.

In the end, the risk matrix (Figure 3.2) is applied in order to assess the level of risk.



	L	M	H	
LIKELIHOOD	P3	P2	P1	6 - 9
	P4	P3	P2	3 - 5
	P5	P4	P3	1 - 2

Figure 3.2 Risk Matrix

With the following risk definitions, and actions required.

- P1= Intolerable risk – work must not be started or continued until the risk has been reduced to an acceptable level.
- P2= Substantial risk which must be improved through risk reduction methods.
- P3= Moderate risk – efforts should be made to reduce the risk within a defined time period.
- P4= Risk is considered tolerable no additional controls required. Monitoring is required to ensure controls are maintained.
- P5= No action required.

3.4 Methodology Review 4: RASE ATEX Risk Assessment

There is EU Project named RASE Project (2000) *"Explosive Atmosphere: Risk Assessment of Unit Operations and Equipment"*. Within their report, a methodology for the risk assessment of unit operations and equipment for use in potentially explosive atmospheres was proposed:

3.4.1 Step 1: Determination of intended use

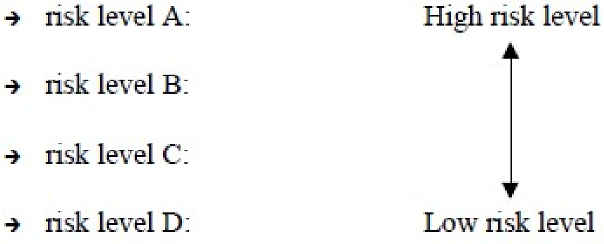
This step needs to be carried out with an understanding of the functioning of the equipment and/or unit operations and the way in which an incident or an accident develops. It includes the description of the system, equipment characteristics, product characteristics, functional analysis.

3.4.2 Step 2: Identification of hazards, hazardous situations and hazardous events

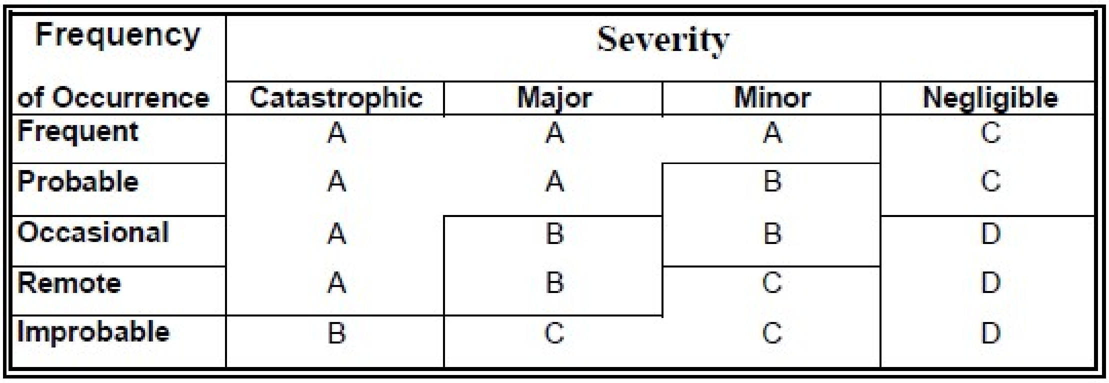
In this step, the emission sources, the type of potentially generated explosive atmosphere, the frequency of occurrence of explosive atmosphere, the presence and effectiveness of ignition sources are considered.

3.4.3 Step 3: Risk estimation

Risk Estimation shall be carried out for each explosion hazard or every hazardous event in turn by determining the elements of risk. In many situations it is not possible to exactly determine all the factors that effect risk, in particular those which contribute to the likelihood of a specified event occurring. Thus risk is often expressed in a qualitative rather than a quantitative way by using the risk matrix (Figure 3.3).



→ risk level A:
→ risk level B:
→ risk level C:
→ risk level D:



Frequency of Occurrence	Severity			
	Catastrophic	Major	Minor	Negligible
Frequent	A	A	A	C
Probable	A	A	B	C
Occasional	A	B	B	D
Remote	A	B	C	D
Improbable	B	C	C	D

Figure 3.3 Frequency-Severity Matrix relating to risk levels

Meanwhile, safety measures and human factors are concerned here. Human factors can affect risk and shall be taken into account in the risk estimation. This may include some of the following aspects: a) interaction of persons with the ATEX products; b) interaction between persons; c) psychological aspects; d) design of the products in relation to ergonomic principles; e) capacity of persons to be aware of risks in a given situation depending on their training, experience and ability.

3.4.4 Step 4: Risk evaluation

Following the risk estimation, Risk Evaluation shall be carried out to determine if Risk Reduction is required or whether safety has been achieved. It is evident. in a risk level of A, the risk is so high as to be intolerable and additional risk reduction measures are required. Similarly a risk level of D can be considered to be acceptable and no further risk reduction is required. Risk levels B and C are intermediate levels and will normally require some form of risk reduction measures to make the risk acceptable.

Thus the risk can be described either as: a) **Intolerable:** If the risk falls into this category then appropriate safety measures must be taken to reduce the risk. or as b) **Acceptable:** If the risk falls into this category then no Risk Reduction is required and the Risk Assessment is complete.

3.5 Methodology Review 5: Manual of the ATEX Directive Application (Cavaliere's Methodology)

Cavaliere and Scardamaglia (2005) and Cavaliere (2011) provided a methodology for the ATEX risk assessment that fulfills the requirements of both ATEX Directive 94/9/EC and related standards.

3.5.1 Step 1: Area classification

The ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures; and it is mainly referred to two standards: IEC 60079-10-1 (for gas, 2008) and IEC 60079-10-2 (for dust, 2009). For specific applications, different countries developed dedicated guidelines, as in Italy CEI 31-35 (2012) and CEI 31-56 (2007).

As a result from Step 1, the internal and external zone classification (Table 3.9) of all identified emission source are determined. Further, with the sum of extension calculation from all external zones (the vertical and horizontal dimensions), the envelop of the external zones are drawn on the layout to understand the critical area. Therefore, the final analysis is completed.

Table 3.9 Area classification depending on the probability of an explosive atmosphere occurrence in a year (CEI 31-35, 2012 & CEI 31-56, 2007)

Area Classification	Probability of Explosive Atmosphere Occurrence in 365 days (PSA)	Descriptor
Zone 0/20	$P>10^{-1}$	Explosive atmosphere is continuously present, for long periods or frequently.
Zone 1/21	$10^{-1}\geq P>10^{-3}$	Explosive atmosphere is sporadically present, during normal operations.
Zone 2/22	$10^{-3}\geq P>10^{-5}$	Explosive atmosphere is not present during normal operations, or infrequently present, for a short period.

3.5.2 Step 2: Ignition source assessment

Ignition source assessment is the second step to go through if the zone classification is determined as a dangerous zone. EN 13463-1 (2009) is a standard for *Non-electrical Equipment for Use in Potentially Explosive Atmospheres*. The standard aims to provide the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres. Following the procedure, the equipment can be verified and marked with ATEX markings for the further use in different ATEX zones' working environment. Since EN 13463-1 covers most common ignition sources and explicates the procedure to identify 13 ignition sources listed in EN 1127-1 (2011), the ignition source assessment takes a part of EN 13463-1 to apply as the method for the ignition source assessment.

3.5.3 Step 3: Damage analysis

The Damage analysis relies on the Area classification result (represented as the ID index which can be determined with the Table 3.10) and other factors: Personnel presence (PL), Dust explosion index (KST), Gas explosion index (KG), Cloud volume (VZ), Layer thickness (SS), Confined Dust Cloud (CN). Given to the guidance of the ATEX risk assessment application (Cavaliere and Scardamaglia, 2005; and Cavaliere, 2011), the formulas and indexes support the calculation of the semi-quantitative parameter D:

$$D = ID + PL + KST + VZ + SS + CN \text{ (for dust)} \qquad \text{Eq. (3.4)}$$

$$D = ID + PL + KG + VZ + CN \text{ (for gas)} \qquad \text{Eq. (3.5)}$$

3.5.4 Step 4: ATEX Risk evaluation

After the P, C, and D values are determined through the results from Step 1 to Step 3, the ATEX Risk evaluation relies on a semi-quantitative approach as in Eq. (3.6).

$$R = P \times C \times D \qquad \text{Eq. (3.6)}$$

According to Table 3.10, the values of P, C, and D can be determined through the results from Step 1 to Step 3. The ATEX risk (R) was the multiplication of P, C, and D ($R = P \times C \times D$), and the final risk level can be ranked (Table 3.11).

Table 3.10 The semi-quantitative ranking system for the ATEX-HOF risk evaluation

Semi-Quantitative Ranking System				
Area Classification Zone	**P**	**Degree**	**C**	**ID**
Zone 0/20	3	Frequently	3	0.6
Zone 1/21	2	Occasionaly	2	0.4
Zone 2/22	1	Rarely	1	0.2
Zone NE	0	N.E.	0	0

Note: 1) The ID value showed in the table is based on the area classification zones and is only the part of the D value calculation; 2) The D value is the sum of ID value and other factors; the maximum value of D for gas situation is 3, and the maximum value of D for dust situation is 3.6.

Table 3.11 ATEX-HOF Risk Evaluation Criteria

Value (R)	Risk Level	Description	Risk Control
$R \geq 18$	High	High likelihood of presence of explosive atmosphere. Ignition sources are present and effective. Consequences of an explosion are extermely serious. Likelihood of explosion propagation is very high.	Risk mitigation measures must be implemented.
$9 \leq R < 18$	Medium	Likely presence of explosion atmosphere and ignition sources can be present and effective. In case of an explosions, consequences are moderate with marginal damage to personnel and process units. Explosion propagation is likely to be moderate.	Risk mitigation measures should be implemented in a short time interval.
$1 \leq R < 9$	Low	The likelihood of presence of an explosive atmosphere is extremely limited, as well as the presence of effective ignition sources. The exposure level is low, so with limited damage to persons and property. The probability of propagation of the explosion is to be considered extremely limited.	Risk mitigation measures should be implemented in a long time interval.
$R \leq 1$	Negligible	Likelihood of explosion atmosphere presence is very unlikely or ignition sources are not present or they are not effective. There are not consequences to personnel or equipment. Explosion propagation is very unlikely to occur.	Operations should be kept monitoring in order to control the risk in this level.

3.6 Discussion: Main Characteristics of Traditional ATEX Risk Assessment Methodologies

From reviewed methodologies, the typical factors concerned with those ATEX risk assessment methodologies are:

a) occurrence of explosive atmospheres: it mainly refers to the standard IEC 60079-10-1 for the explosive gas atmosphere and IEC 60079-10-2 for the explosive dust atmosphere;

b) effectiveness of ignition sources: it mainly refers to the standard EN 1127-1 and EN 13463-1 mentioned by some methodologies;

c) consequence: this part has various consideration depending on different methodologies. Some methodologies recommend mathematic modelling; some consider indexes; and some have taken into account of the impact on human. The major considerations are: exposure and duration of workers, dangerous distance and overpressure, etc.

Not all methodologies treated safety measures as an independent factor, but they consider safety measures within the assessment of other factors (e.g. occurrence of explosive atmosphere, assessment of ignition sources).

Most of those ATEX Risk Assessment methodologies handle HOF within the consequence analysis. It mainly focuses on the impact on human, such as the exposure and duration time of workers, the potential injury, and so on. However, the influence from HOF on the ATEX hazards, although only RASE ATEX risk assessment methodology mentioned, has been not dealt with specific procedures within those reviewed methodologies.

Chapter 4. The ATEX-HOF Methodology

Integration of HOF into the ATEX Risk Assessment Methodology

Chapter Objectives:

4.1 The ATEX-HOF Methodology

4.2 Application of HRA Techniques into ATEX Risk Assessment: from THERP to FUZZY CREAM

Chapter 4. The ATEX-HOF Methodology

4.1 The ATEX-HOF Methodology

Cavaliere and Scardamaglia (2005) and Cavaliere (2011) provided a methodology for the ATEX risk assessment that fulfills the requirements of both ATEX Directive 94/9/EC, Directive 99/92/EC and related standards. However, when reviewing the ATEX risk assessment procedures, despite many operations on plant and equipment containing dangerous substances are performed by operators, the influence of human and organizational factors (HOF) are neglected (e.g. maintenance activity). Here, the ATEX-HOF methodology is proposed based on the traditional methodology, with the aim of providing an advanced methodology to analyze HOF influences on ATEX hazards. The framework of the ATEX-HOF methodology is developed with four steps: 1) Area classification, 2) Ignition source identification, 3) Damage analysis, and 4) ATEX Risk evaluation (Figure 4.1).

The original ATEX Risk assessment relies on a semi-quantitative approach as in Eq. (4.1).

$$R = P \times C \times D \qquad \text{Eq. (4.1)}$$

The ATEX risk (R) is a function of the following parameters: probability of an explosive atmosphere formation (P), probability of an effective ignition source presence (C), and possible damages (D). The ATEX-HOF methodology was aimed at identifying the HOF influence in each step, and providing an integrated safety assessment approach. The ATEX-HOF risk evaluation is still using the semi-quantitative approach as in Eq. (4.2):

$$R_{HOF} = P_{HOF} \times C_{HOF} \times D_{HOF} \qquad \text{Eq. (4.2)}$$

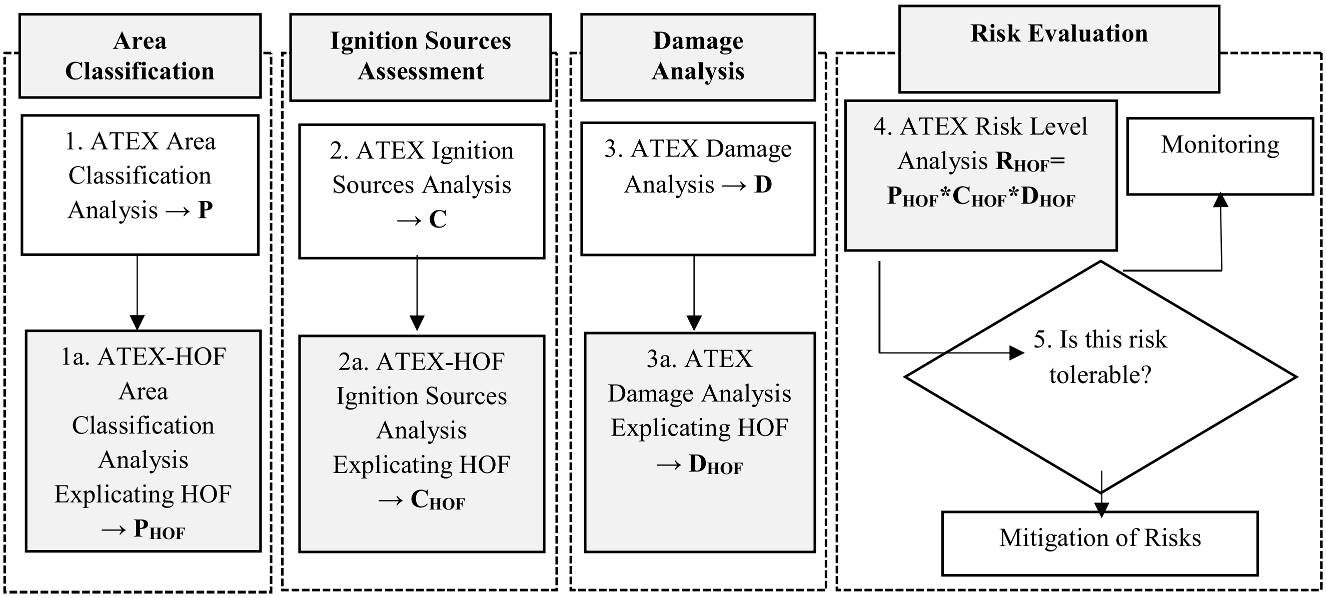


Figure 4.1 The framework of the ATEX-HOF methodology (Geng, et al., 2015a)

4.1.1 Step 1: ATEX-HOF Area Classification

The area classification has been carried out when the initial process and instrumentation line diagrams and initial layout plans were available and confirmed before plant start-up. The ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures; and it is mainly referred to two standards: IEC 60079-10-1 (for explosive gas atmosphere, 2008) and IEC 60079-10-2 (for explosive dust atmosphere, 2009). For specific applications, different countries developed dedicated guidelines, as in Italy CEI 31-35 (2012) and CEI 31-56 (2007). Since the procedures conducting risk assessment for the explosive gas atmosphere and the explosive dust atmosphere are similar, here, the Area classification procedures for the explosive gas atmospheres are chosen to show in details.

Step 1-1: Identification of source of release

The basic elements for establishing the hazardous zone are identifying the source of release and determining the grade of release. Since an explosive gas atmosphere can exist only if a flammable gas or vapour is present with air, it is necessary to decide if any of these flammable materials can exist in the area concerned. Each item of the process equipment which contains flammable materials is considered as a potential release source, such as a tank, pump, pipeline, vessel, etc.

Step 1-2: Determining the area classification inside the equipment

Normally, the type of the area classification inside the equipment (the internal zone) can be referred to the grade of release (IEC 60079-10-1, 2008): a) *a continuous grade of release* is expected to occur frequently or for long periods, and leads to a zone 0; b) *a primary grade of release* can be expected to occur periodically or occasionally during normal operation, and leads to zone 1; c) *a secondary grade of release* is not expected to occur in normal operation and, if it does occur, is likely to do so only infrequently and for short periods, leads to zone 2.

Further, the flammable substances released into the atmosphere can be diluted by dispersion or diffusion into the air until its concentration is below the Lower Explosive Limit (LEL). Ventilation helps promoting dispersion, and Table 4.1 shows the influence of the ventilation on determining the type of zone. The effectiveness of the ventilation will depend upon the degree and availability of ventilation and the design of the system.

Three *degrees of ventilation* are recognized: a) *High ventilation (VH)* can reduce the concentration at the source of release virtually instantaneously, resulting in a concentration below the lower explosive limit; further, leading to a negligible extent result. b) *Medium ventilation (VM)* can control the concentration, resulting in a stable zone boundary, whilst the release is in progress, and where the explosive gas atmosphere does not persist unduly after the release has stopped. c) *Low ventilation (VL)* cannot control the concentration whilst release is in progress and/or cannot prevent undue persistence of a flammable atmosphere after release has stopped.

Meanwhile, three levels of *availability of the ventilation* should be considered: a) *Good* ventilation is present virtually continuously; b) *Fair* ventilation is expected to be present during normal operation. Discontinuities are permitted provided they occur infrequently and for short periods; c) *Poor* ventilation which does not meet the standard of fair or good, but discontinuities are not expected to occur for long periods. Ventilation that does not even meet the requirement for poor availability must not be considered to contribute to the ventilation of the area (IEC 60079-10-1, 2008).

Table 4.1 Influence of the ventilation on type of zone (IEC 60079-10-1, 2008)

Grade of release	**Ventilation**						
	Degree						
	High			**Medium**			**Low**
	Availability						
	Good	**Fair**	**Poor**	**Good**	**Fair**	**Poor**	**Good, Fair or Poor**
Continuous	(Zone 0 NE) Non-hazardous[a]	(Zone 0 NE) Zone 2[a]	(Zone 0 NE) Zone 1[a]	Zone 0	Zone 0 + Zone 2	Zone 0 + Zone 1	Zone 0
Primary	(Zone 1 NE) Non-hazardous[a]	(Zone 1 NE) Zone 2[a]	(Zone 1 NE) Zone 2[a]	Zone 1	Zone 1 + Zone 2	Zone 1 + Zone 2	Zone 1 or Zone 0[c]
Secondary[b]	(Zone 2 NE) Non-hazardous[a]	(Zone 2 NE) Non-hazardous[a]	Zone 2	Zone 2	Zone 2	Zone 2	Zone 1 and even Zone 0[c]

NOTE 1 “+’ signifies “surrounded by’.

NOTE 2 Particular care should be taken to avoid situations where enclosed areas containing sources that give only secondary grades of release might be classified as zone 0. This applies also to small non-purged and non-pressurized enclosed areas, e.g. instrument panels or instrument weather protection enclosures, thermally insulated heated enclosures or enclosed spaces between pipe installations and envelope of thermal insulation. Such enclosures should preferably be provided with at least some kind of appropriately located apertures that will enable unimpeded movement of air through the interior. Where that is not possible, practicable or desirable, effort should be made to keep major potential sources of release out of enclosures, e.g. pipe connections should normally be kept out of insulation enclosures as well as any other equipment that may be considered a potential source of release.

NOTE 3 Continuous and primary sources of release should preferably not be located in areas with a low degree of ventilation. Either sources of release should be relocated, ventilation should be improved or the grade of release should be reduced.

NOTE 4 The summation of sources of release with regular (i.e. well predictable) activity should be based on detailed analysis of operating procedures. For example, *N* sources of release with common mode of release should be normally considered as a single source of release with *N* different discharge points.

[a] Zone 0 NE, 1 NE or 2 NE indicates a theoretical zone which would be of negligible extent under normal conditions.

[b] The zone 2 area created by a secondary grade of release may exceed that attributable to a primary or continuous grade of release; in this case, the greater distance should be taken.

[c] Will be zone 0 if the ventilation is so weak and the release is such that in practice an explosive gas atmosphere exists virtually continuously (i.e. approaching a ’no ventilation” condition).

Step 1-3: Determining the area classification outside the equipment

1) Initial External Zone Determination

Determining the area classification outside the equipment (the external zone) is based on the release rate, LEL, ventilation and other factors and the estimated (or calculated) area over which the explosive atmosphere insists before it disperses. Relevant standards and national guidelines (e.g. IEC 60079-10-1, 2008; CEI 31-35, 2012) shows the technical procedures and information to perform the initial external zone determination. Here are some important factors that can influence the external zone determination:

a) *Release Rate of Gas or Vapour:* The greater the release rate, the larger the extent of the zone. The release rate depends itself on other parameters, namely and specifically for a methane release, like in the case under study: *a1) Geometry of the source of release.* This is related to the physical characteristics of the source of release, for example, an open surface, leaking flange, etc. *a2) Release velocity.* For a given source of release, the release rate increases with the release velocity. In the case of a product contained within process equipment, the release velocity is related to the process pressure and the geometry of the source of release. The size of a cloud of flammable gas or vapour is determined by the rate of flammable vapour release and the rate of dispersion. Gas and vapour flowing from a leak at high velocity will develop a cone-shaped jet, which will entrain air and be self-diluting. The extent of the explosive gas atmosphere will be almost independent of air flow. If the material is released at low velocity or if its velocity is reduced by impingement on a solid object, it will be carried by the air flow and its dilution and extent will depend on air flow. *a3) Concentration.* The release rate increases with the concentration of flammable vapour or gas in the released mixture.

b) *Lower Explosive Limit (LEL):* For a given release volume, the lower the LEL the greater will be the extent of the zone.

c) *Ventilation:* With increased ventilation, the extent of the zone will normally be reduced. Obstacles, which impede the ventilation, may increase the extent of the zone. On the other hand, some obstacles, for example, dykes, walls or ceilings, may limit the extent.

d) *Relative Density of the Gas or Vapour When It Is Released:* If the gas or vapour is significantly lighter than air, it will tend to move upwards. If significantly heavier, it will tend to accumulate at ground level. The horizontal extent of the zone at ground level will increase with increasing relative density and the vertical extent above the source will increase with decreasing relative density.

e) *Other Parameters to Be Considered: e1) Climatic conditions:* The rate of gas or vapour dispersion in the atmosphere increases with wind speed but there is a minimum speed of 2 m/s – 3 m/s required to initiate turbulent diffusion; below this, layering of the gas or vapour occurs and the distance for safe dispersal is greatly increased. *e2) Applied Barriers:* The release and the spreading of the flammable substances can be prevented by barriers: technical barriers (e.g. grounding system), human interventions (e.g. maintaining activities), and sufficient ventilation.

2) Estimation of probability of failure of applied barriers and relevant operational activities

The release and the spreading of flammable substances can be influenced by suitable barriers (technical barriers and/or operational barriers), sufficient ventilations, and other relevant human interventions. Apart from the ventilation condition handling by the specific procedure, other relevant operational activities and/or applied barriers are addressed via the quantitative approach. Both the extension and the probability of occurrence of the external flammable cloud must be determined with the consideration of those applied barriers and other relevant operations which have potential probability to fail (Pr_{BF}). In details,

a) *a probability of a technical barrier failure (P_{tbf})* can be estimated by using the function analysis with relevant technical documents;
b) *a probability of an operational barrier failure (HEP)* can be estimated by applying human reliability analysis (HRA) techniques (e.g. FUZZY CREAM). Operational barriers are the specific activities especially for the safety prevention and protection (e.g. safety audit, safety inspection, etc.).
c) *a probability of other operational failure (HEP)* can be estimated as the well as the operational barrier failure. Those operational activities are those daily tasks performing by operators/maintainers, in order to keep the system running in a normal operation condition.

3) Event tree analysis and Final external zone determination

The Event tree (Papazoglou, 1998) is here introduced for a probabilistic safety assessment (PSA). The initial event (Figure 4.2) has an initial probability (Pr_{IN}) that represents the internal explosive atmosphere occurrence. A series of possible paths are constructed by applied barriers and relevant operational activities. Each path is assigned with a probability of failure (Pr_{BF}) or success (Pr_{BS}).

The probability allows to calculate the likelihood of having an initial/additional explosive atmosphere (PSA). Where the Pr_{IN} is not available, otherwise, the initial probability can be assessed starting from the internal zone classification, according to Table 4.2 that correlates the area classification to the probability of their presence.

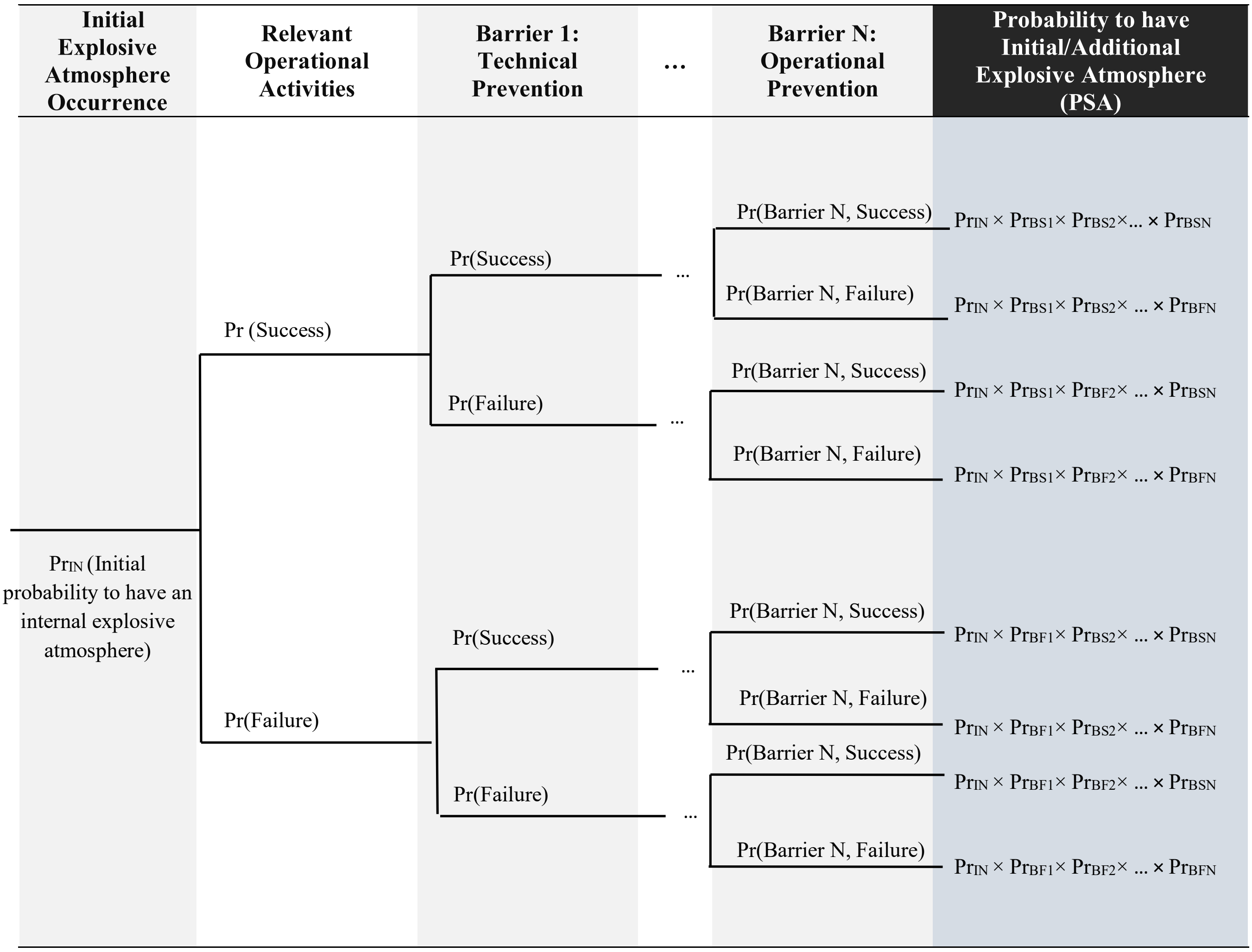


Figure 4.2 Event tree structure for the external zone determination

Table 4.2 Area classification depending on the probability of an explosive atmosphere occurrence in a year (CEI 31-35, 2012 & CEI 31-56, 2007)

Area Classification	Probability of Explosive Atmosphere Occurrence in 365 days (PSA)	Descriptor
Zone 0/20	$P>10^{-1}$	Explosive atmosphere is continuously present, for long periods or frequently.
Zone 1/21	$10^{-1}\geq P>10^{-3}$	Explosive atmosphere is sporadically present, during normal operations.
Zone 2/22	$10^{-3}\geq P>10^{-5}$	Explosive atmosphere is not present during normal operations, or infrequently present, for a short period.

Step 1-4: Results of the ATEX-HOF Area classification

As a result, all identified release sources from both internal and external zone classification of any equipment are summarized (Table 4.3). Further, with the sum of extension calculation from all external zones (the vertical and horizontal dimensions), the envelop of the external zones are drawn on the layout to understand the critical area. Therefore, the final analysis is completed.

Table 4.3 ATEX-HOF Area classification result

Emission Source	**Internal Source of Release**	**Internal Grade of Release**	**Internal Zone**	**External Source of Release**	**External Grade of Release**	**Relevant Operational Activities and/or Applied Barriers**	**PSA** (Probability to have additional explosive atmosphere)	**External Zone**
E.S.	S.R.	Continuous/ Primary/ Secondary	Zone 0/20, Zone 1/21, Zone 2/22, Zone NE	S.R.	Continuous/ Primary/ Secondary	Technical Barriers/ Operational Barriers/ Other relevant operational activities	Integration of : 1) the initial probability (Pr_{IN}); and 2) Prob. of Barrier/operational Failure (e.g. HEP, P_{tbf})	Zone 0/20, Zone 1/21, Zone 2/22, Zone NE

4.1.2 Step 2: ATEX-HOF Ignition Source Assessment

Ignition source assessment is the second step to go through if the zone classification is determined as dangerous zone. EN 13463-1 (2009) is a standard for *Non-electrical Equipment for Use in Potentially Explosive Atmospheres*. The standard aims to provide the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres. Following the procedure, the equipment can be verified and marked with ATEX markings for the further use in different ATEX zones' working environment. Since EN 13463-1 covers most common ignition sources and explicates the procedure to identify 13 ignition sources listed in EN 1127-1 (2011), ATEX-HOF methodology takes a part of EN 13463-1 to apply as the method for the ignition source assessment. General procedures include:

Step 2-1: Presence of potential ignition sources

EN 13463-1 (2009) provides a scheme for the ignition source identification, and defines four types of ignition sources and their relationship (Figure 4.3).

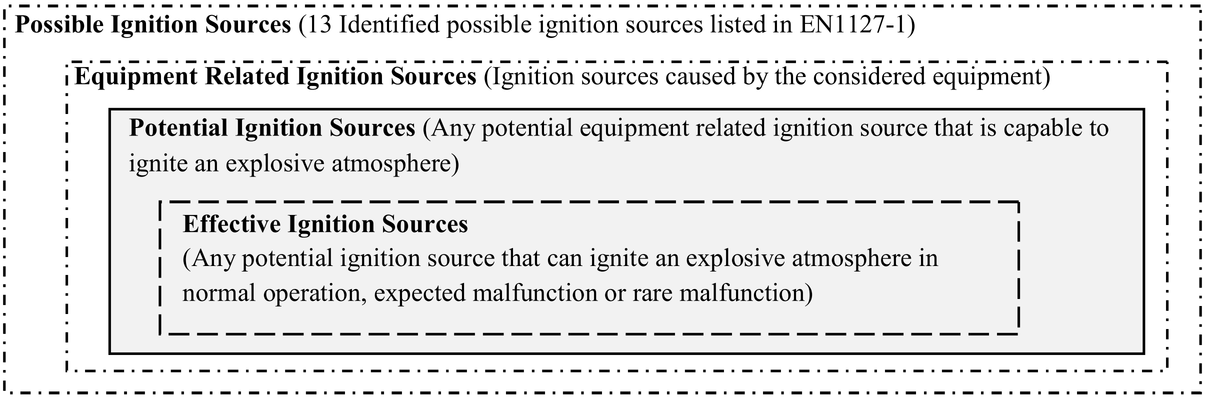


Figure 4.3 Relationship of four types of ignition sources (EN 13463-1, 2009)

Potential ignition sources are identified based on 13 possible ignition sources listed in EN 1127-1 (Table 4.4).

Table 4.4 Possible ignition sources according to EN 1127-1 (2011)

- Hot surfaces	- Electromagnetic waves
- Flames, hot gases	- Ionizing radiations
- Mechanical sparks	- High-frequency radiation
- Sparks from electrical equipment	- Ultrasounds
- Static electricity	- Adiabatic compression
- Catholic protection and corrosion protection	- Chemical reactions
- Lightning	

Once the presence of the ignition source is identified, the frequency of occurrence will be assessed (EN 13463-1, 2009):

1) occurrence *during normal operation* is the situation when the equipment are operating for their intended use within their design parameters;
2) occurrence *during foreseeable malfunction* is the situation when the equipment/person do not perform the intended function/tasks; and such disturbances are known to occur in practice;
3) occurrence *during rare malfunction* is the situation that type of malfunction caused by equipment and/or person may happen only in rare instances;
4) *not relevant* is applied when the situation is not mentioned among those three categories above.

Step 2-2: Effective ignition sources assessment

It is known that one has to supply initial ignition energy to initiate combustion process in a flammable mixture air. A flammable mixture air can be ignited by an external source of energy such as electric spark, a naked flame, hot vessel walls, compression, etc. It is possible to ignite any flammable mixture only when the maximum generated energy is enough to ignite the mixture (above the minimum ignition energy, MIE). Normally, it could be conducted quantitatively, but more often, it can be conducted in the qualitative way. For example, in order to have an effective hot surface, the maximum surface temperature under the most adverse operation condition should be taken into account. For some of the ignition sources, specific standards exist to support their assessment, as the standard CLC/TR 50404 (2003) for the static electricity.

Table 4.5 Potential and effective ignition sources identification (developed from EN 13463-1, 2009)

No.	1		2					3
	Potential Ignition Sources		**Assessment of the frequency of occurrence without applied barriers**					**Effectiveness (Y/N)**
	a	b	a	b	c	d	e	
	Potential Ignition Sources	Description/ Basic Cause	During normal operation	During foreseeable malfunction	During rare malfunction	Not relevant	Reasons for assessment	

Step 2-3: Event tree analysis and final ignition likelihood estimation

In case that identified potential ignition source is effective, applied barriers should be considered. Event tree is built (Figure 4.4). The initial event is characterized by the initial probability of the ignition source presence (Pr_{IG}). Series paths are constructed by applied barriers and/or relevant operational activities. The probability of failures can be result from the technical barrier failure (Pr_{tbf}) and/or human interventions (HEP). The probability allows to calculate the likelihood of having an initial/additional effective ignition sources. Since the initial assessment of the ignition source presence is a qualitative value, it cannot be calculated directly in the Event tree. Different from Area classification that can take advantage of probability indexes from Italian Guidelines, the ATEX-HOF Ignition source assessment linked with the uniform probability ranges from the Area classification (Table 4.6).

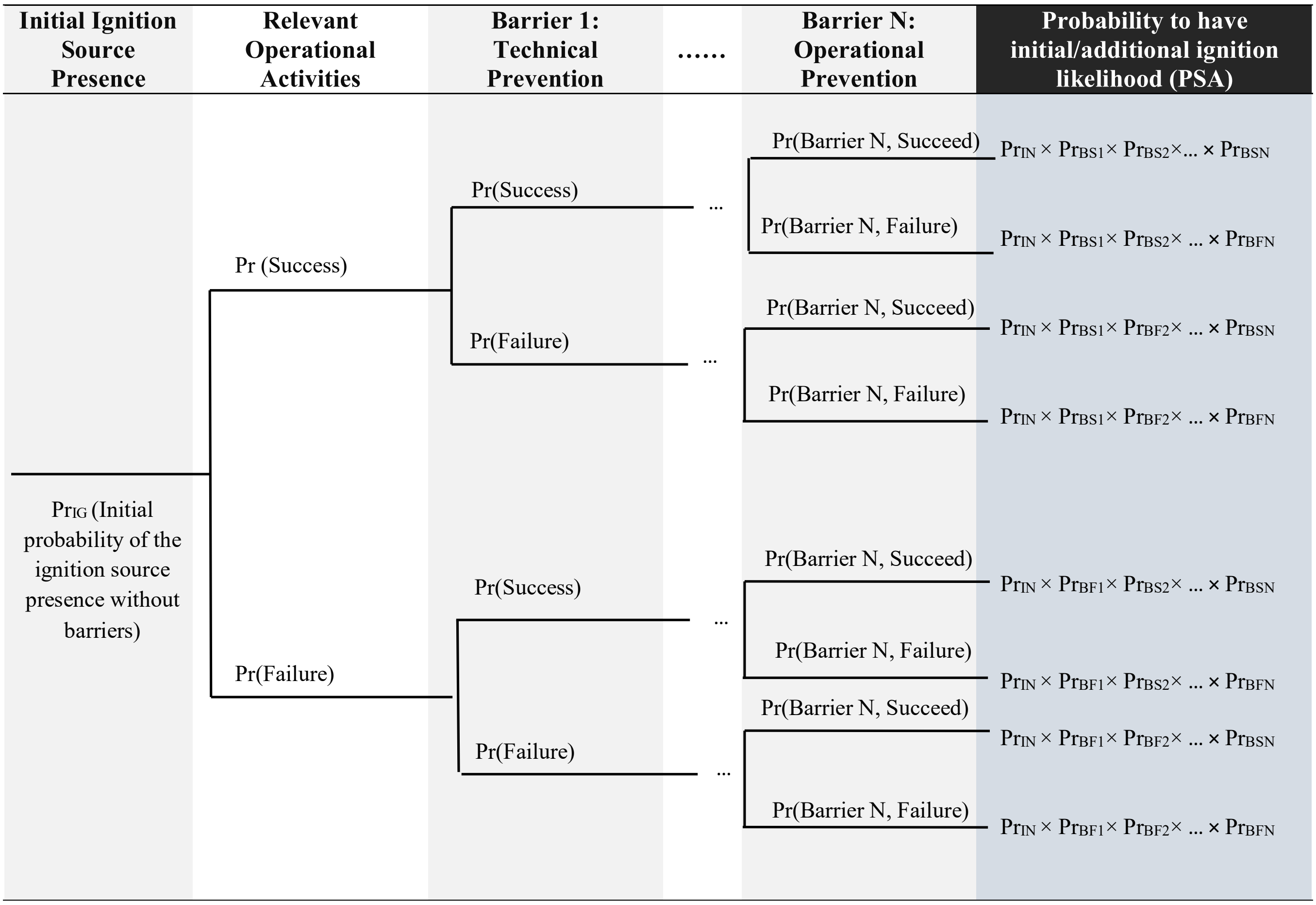


Figure 4.4 Event tree structure for the ignition likelihood determination

Table 4.6 Linking probability ranges with the frequency of occurrence

Ignition Likelihood	Frequency of Occurrence Assessment for Ignition Sources (EN 13463-1, 2009)	Probability of Explosive Atmosphere Formation in 365 days (CEI 31-56, 2007; CEI 31-35, 2012)	Area Classification
Frequently	During normal operation	$P>10^{-1}$	Zone 0/20
Occasionally	During foreseeable malfunction	$10^{-1}\geq P>10^{-3}$	Zone 1/21
Rarely	During rare malfunction	$10^{-3}\geq P>10^{-5}$	Zone 2/22
N.E.	Not relevant	$10^{-5}>P$	Zone NE

Step 2-4: ATEX-HOF Ignition source assessment result

The ATEX-HOF Ignition source assessment of each emission source is assessed in the conservative way. The maximum value of the ignition likelihood among all identified potential ignition sources will be chosen as the final result (Table 4.7).

Table 4.7 Final ignition likelihood estimation (developed from EN 13463-1, 2009)

4			5	6				7
Measures applied to prevent the ignition source becoming effective			**PSA**	**Frequency of occurrence including applied measures**				**Ignition Likelihood**
a	b	c		a	b	c	d	
Description of the measure applied	Basis (citation of standards, technical rules, experimental results)	Technical documentation		During normal operation	During foreseeable malfunction	During rare malfunction	Not relevant	

4.1.3 Step 3: ATEX-HOF Damage Analysis

The Damage analysis relies on the Area classification result (represented as the ID index which can be determined with the Table 4.9) and other factors (Table 4.8): Personnel presence (PL), Dust explosion index (KST), Gas explosion index (KG), Cloud volume (VZ), Layer thickness (SS), Confined Dust Cloud (CN). Given to the guidance of the ATEX risk assessment application (Cavaliere and Scardamaglia, 2005; and Cavaliere, 2011), the formulas and indexes support the calculation of the semi-quantitative parameter D_{HOF}. If the zone prediction changes in the ATEX-HOF Area classification, the ID value is also changed as ID_{HOF}.

$$D_{HOF} = ID_{HOF} + PL + KST + VZ + SS + CN \text{ (for dust)} \qquad \text{Eq. (4.3)}$$

$$D_{HOF} = ID_{HOF} + PL + KG + VZ + CN \text{ (for gas)} \qquad \text{Eq. (4.4)}$$

Table 4.8 Indexes for the D'_{HOF} value estimation (Cavaliere, 2011)

Factors	**Unit of Factors**	**Indexes**			
		0	**0.2**	**0.4**	**0.6**
		Zone NE	**Zone 2 or Zone 22**	**Zone 1 or Zone 21**	**Zone 0 or Zone 20**
Personnel presence (PL)	--	Absent of Work	Occasional Work	Intermittent Work	Continuous Work
Dust explosion index (Kst)	(bar × m/s)	< 10	10 to 50	51 to 100	> 100
Gas explosion index (KG)	(bar × m/s)	< 10	10 to 50	51 to 100	> 100
Cloud volume (VZ)	(dm^3)	0	≤ 1	1 ≤ 10	> 10
Layer thickness (SS)	(mm)	Absent	≤ 5	5 ≤ 50	> 50
Confined Dust Cloud (CN)	--	Not Expected	Not Confined	Partly Confined	Completed Confined

4.1.4 Step 4: ATEX-HOF Risk Evaluation

According to Table 4.9, the values of P_{HOF}, C_{HOF}, and D_{HOF} can be determined through the results from Step 1 to Step 3. The ATEX-HOF risk (R_{HOF}) is the multiplication of P_{HOF}, C_{HOF}, and D_{HOF} ($R_{HOF} = P_{HOF} \times C_{HOF} \times D_{HOF}$). Once the R_{HOF} is calculated, relevant decision making on the safety control can be conducted (Table 4.10).

$$R_{HOF} = P_{HOF} \times C_{HOF} \times D_{HOF} \qquad \text{Eq. (3.6)}$$

Table 4.9 The semi-quantitative ranking system for the ATEX-HOF risk evaluation

Area Classification Zone	**Probability of Explosive Atmosphere Formation in 365 days (CEI 31-56, 2007)**	**Semi-Quantitative Ranking System**			
		Degree	**P or P_{HOF}**	**C or C_{HOF}**	**ID or ID_{HOF}**
Zone 0/20	$P>10^{-1}$	Frequently	3	3	0.6
Zone 1/21	$10^{-1}\geq P>10^{-3}$	Occasionaly	2	2	0.4
Zone 2/22	$10^{-3}\geq P>10^{-5}$	Rarely	1	1	0.2
Zone NE	$10^{-5}>P$	N.E.	0	0	0

Note: 1) The ID_{HOF} value showed in the table is based on the area classification zones and is only a part of the D_{HOF} value calculation; 2) The D_{HOF} value is the sum of ID_{HOF} value and other factors showed in Table 4.8; the maximum value of D_{HOF} for gas situation is 3, and the maximum value of D_{HOF} for dust situation is 3.6.

Table 4.10 ATEX-HOF Risk Evaluation Criteria

Value (R_{HOF})	**Risk Level**	**Description**	**Risk Control**
$R_{HOF} \geq 18$	High	High likelihood of presence of explosive atmosphere. Ignition sources are present and effective. Consequences of an explosion are extermely serious. Likelihood of explosion propagation is very high.	Risk mitigation measures must be implemented.
$9 \leq R_{HOF} < 18$	Medium	Likely presence of explosion atmosphere and ignition sources can be present and effective. In case of an explosions, consequences are moderate with marginal damage to personnel and process units. Explosion propagation is likely to be moderate.	Risk mitigation measures should be implemented in a short time interval.
$1 \leq R_{HOF} <9$	Low	The likelihood of presence of an explosive atmosphere is extremely limited, as well as the presence of effective ignition sources. The exposure level is low, so with limited damage to persons and property. The probability of propagation of the explosion is to be considered extremely limited.	Risk mitigation measures should be implemented in a long time interval.
$R_{HOF} \leq 1$	Negligible	Likelihood of explosion atmosphere presence is very unlikely or ignition sources are not present or they are not effective. There are not consequences to personnel or equipment. Explosion propagation is very unlikely to occur.	Operations should be kept monitoring in order to control the risk in this level.

4.2 Application of HRA techniques into ATEX Risk Assessment: From THERP to FUZZY CREAM

In order to analyse the effectiveness of human interventions, the *Event tree* based *probabilistic safety assessment (PSA)* has been introduced in the ATEX-HOF Methodology. The initial event has an initial probability (Pr_{IN}/Pr_{IG}) that represents the internal explosive atmosphere occurrence (or the ignition source presence). A series of possible paths are constructed by applied barriers and relevant operational activities. Each path is assigned with a probability of failure (Pr_{BF}) or success (Pr_{BS}). A probability of a technical barrier failure is suggested to apply functional analysis; and the probability of operational failure is using Human Reliability Analysis (HRA) techniques.

Stanton et al. (2005) conducted literature review that any method discovered was recorded and added to the database. The result of this initial literature review was a database of over 200 HF methods and techniques (Table 2.4 in Chapter 2). Considering even a simple interactive system, this requires an examination of the links between every possible cause and every possible consequence, it is impossible in practice to make a deterministic analysis. The common solution is to conduct a probabilistic analysis for instead (Hollnagel, 1998). Human reliability analysis (HRA) techniques, as one of the important categories in the human factor techniques, aims to identify and quantify human error (Balfe, 2015).

Evans (1976) explained that **human reliability** is a probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system. **Human reliability analysis (HRA)** is a method that human reliability is estimated. Among the reviewed HRA techniques in Chapter 2, THERP, SPAR-H, NARA, CREAM, HEART, and ATHEANA can support quantitative analysis. NASA (2010) compared three HRA techniques: 1) THERP (the Technique for Human Error Rate Prediction; Swain and Guttman, 1983), 2) CREAM (Cognitive Reliability and Error Analysis Method; Hollnagel, 1998), and 3) NARA (Nuclear Action Reliability Assessment; Kirwan, et. al, 2005); and Nespoli & Ditali (2010) compared THERP and HEART (Human Error Assessment and Reduction Technique; Williams, 1992). As their conclusions, "THERP, as one of the HRA techniques, although it is not a very recent method, was proved to be still valid and efficient to well represent human error rate range, if a quantitative estimate is required".

In addition, SPAR-H, The Standard Plant Analysis Risk-Human Reliability Analysis (NUREG/CR-6883; Gertman et al., 2005), was developed as a further simplification of THERP. The basis for quantification of the Performance Shaping Factors (PSFs) is grounded in THERP (Boring and Blackman, 2007). As with THERP, quantification in SPAR-H has not been validated against newer technology applications (Boring and Gertman, 2012).

A Technique for Human Error Analysis (ATHEANA; Forester et al., 2007) does not include a formal list of PSFs, and it uses expert estimation to generate HEPs. In practice, this approach has required considerable expertise and may be subject to greater inter-analyst variability than THERP (Forester et al., 2006).

CREAM - Cognitive Reliability and Error Analysis Method (Hollnagel, 1998), covers technical, human and organizational factors, and provides a relatively stable Human Error Probability (HEP) output (Chandler, et. al, 2006). The framework is described as a Method-Classification-Model (MCM). CREAM has not been developed from the underlying model of cognition, but simply uses it as a convenient way to organize some of the categories that describe possible causes and effects in human actions. It was designed for different types of industries. CREAM provides two methods that can be used to calculate Human Error Probability (HEP): the basic method and the extended method.

As mentioned above, both THERP and CREAM are applied and compared in this study, in order to investigate their performance on the estimation of Human Error Probability (HEP) in the on-site application.

4.2.1 THERP Application

4.2.1.1 Description of THERP

It is the first total approach used in the field of Human Reliability Analysis (HRA) domain. It is designed for nuclear power plants. THERP is one of typical methods of Task-dominant type HRA techniques. It considers the only one dominant factor to HEP, the nominal HEP is determined once the task is known, and the nominal HEP can be modified by other factors (PSFs) later. THERP, although it is not a very recent method, was proved to be still valid and efficient to well represent human error rate range, if a quantitative estimate is required (Swain & Guttmann, 1983).

According to the Handbook of THERP developed by Swain and Guttmann (1983), human can be considered as a closed-loop system component that can receive the information from external environment (such as working environment, documentation materials, displays, etc.), and transfer those external inputs into the internal inputs of human component inside. Inside, human receives internal inputs via sensing, discrimination, and perceiving; then, processes internal inputs based on cognitions; and, responses as human outputs to system outside; finally, external results are obtained. During the internal inputs processing, three human behaviors would influence the performance of human: skill-based behavior, rule-based behavior, and knowledge-based behavior. As a result, those influences may cause incorrect outputs as human errors considering omissions and commissions.

4.2.1.2 THERP Application

A dust cartridge filter was chosen as the case study. This case study was original from a food manufacturing plant. The plant produces food stabilizers, ingredients, starches and gums. The dust cartridge filter needs to be replaced regularly according to the frequency of use mentioned in the maintenance instructions. Lack or failure to replace, dust accumulation inside the filter could break other machines and produce internal and external explosive atmosphere.

For quantifying the HEP, the basic tool of THERP is a form of event tree as human error tree. The branches of the human error tree represent a binary decision process which the correct or incorrect performance are the only choices. For each choice, HEP could be estimated by referring to the 27 tables from the THERP handbook. Thus, the final HEP of the whole tree can be obtained based on the Bayesian method.

Step 1. Task Analysis

Operators or maintainers are always replacing the filter in a correct way. If considering such activity fails with a certain probability, task analysis is applied to identify potential risks caused by human errors. The list of human actions is as the following:

Relevant Steps from “Immediate Actions” to guarantee the success of doing replacement:
Step 1. Verify the need to replace GV5 based on the frequency of use.
Step 2. Verify if the replacement action has been done or not.

Relevant Steps from “Follow-up Actions” to guarantee the success of doing replacement:
Step 3. In case of lack of replacement, proceed with the replacement action.
Step 3.1 Remove the cartridge cover and clean the dust.
Step 3.2 Remove the used cartridges and replace them, reminder to connect the copper present on the same track.
Step 3.3 Check the solenoid firing.
Step 3.4 Check the cleanliness of the cabinet.

Step 2. Human Error Tree Analysis

The calculation is based on the HRA event tree (human error tree) and Bayesian method. Figure 4.5 presents the human error tree for the Problem 1. Three branches show three human actions identified by the task analysis. F1, F2 and F3 represent step 1, step 2, and step 3.

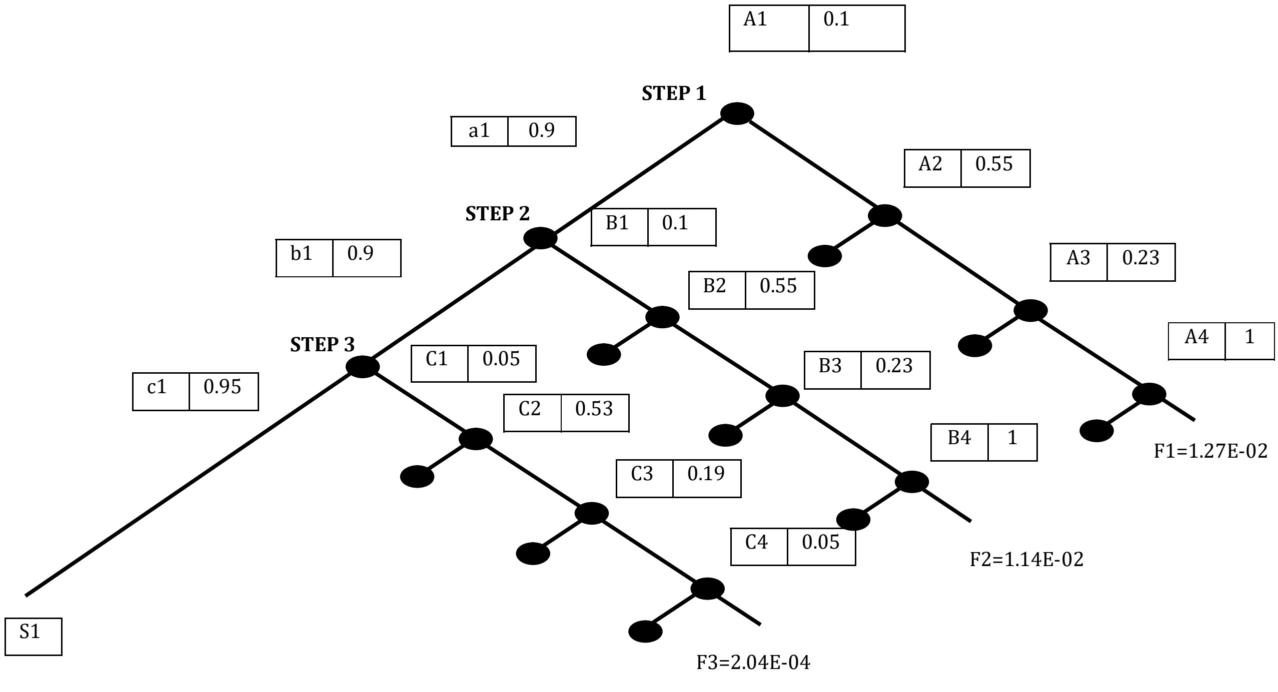
In the handbook, table 20-4 lists assumptions of "number of reactor operators and advisors available to cope with an abnormal event and their related levels of dependence". These assumptions enable the analyst to consider the effects of personnel interaction in modifying the nominal HEPs for post-event activities. The time interval for response of an abnormal event has four classifications:

1) 0-1 minute: only on-duty reactor operator (RO) could response;
2) at 1 minute, on-duty reactor operator (RO) and senior reactor operator (SRO) could be involved;

3) at 5 minutes, on-duty reactor operator (RO) and senior reactor operator (SRO) and shift supervisor (SS) could be involved;

4) at 15 minutes, reactor operator (RO), senior reactor operator (SRO), shift supervisor (SS) and shift technical advisor (STA) could be involved. For each branch (each human action), the analyst supposes that the diagnosed time for the abnormal situation is at 15 minutes.

Thus, four reactor operators and advisors should be available to cope with such abnormal event, and they are represented by the nodes on each branch (Table 4.11). In terms of the Bayesian method, a binary decision process which the correct or incorrect performance are the only choices for each node. Therefore, among three failure braches in the HRA event tree, two failure braches (F1 and F2) of immediate actions are clearly dominant. These two failure braches contribute to almost the overall failure probability F_T, of 2.43×10^{-2}.



F_T = F1+F2+F3= 2.43E-02

Figure 4.5. Human Error Tree for Problem 1

Table 4.11 Explanation of terms in HRA event tree for Problem 1

Failure Node & Person	Estimated HEP and Source	Task Explanation
A1	0.1	RO failed to correctly diagnose the need to replace the filter based on the frequency.
A2	0.55	SRO failed to correctly diagnose the need to replace the filter based on the frequency.
A3	0.23	SS failed to correctly diagnose the need to replace the filter based on the frequency.
A4	1	STA failed to correctly diagnose the need to replace the filter based on the frequency.
B1	0.1	RO failed to verify if the replacement action has been done or not.
B2	0.55	SRO failed to correct RO’s error.
B3	0.23	SS failed to correct RO’s error.
B4	1	STA would not be involved in this procedural detail.
C1	0.05	RO failed to do replacement action step by step correctly.
C2	0.53	SRO failed to correct RO’s error.
C3	0.19	SS failed to correct RO’s error.
C4	0.05	STA failed to start some mitigation measures for responding RO, SRO, and SS’s error.

4.2.2 FUZZY CREAM Application

4.2.2.1 Description of CREAM

Cognitive Reliability and Error Analysis Method (CREAM) is the representative of cognition-dominant HRA methods which was developed. CREAM is a generic term, and includes environment, task characteristics, operator and plant, etc. It considers interactions between person-related, technology-related, and organization-related factors; and provides a relatively stable HEP output; also, it was designed for different types of industries (Chandler, et. al, 2006).

The framework is described as a **Method-Classification-Model (MCM)**. CREAM has not been developed from the underlying model of cognition, but simply uses it as a convenient way to organize some of the categories that describe possible causes and effects in human actions (Hollnagel, 1998). *The model* is to define the relationship between components of the classification scheme. It is the way in which erroneous actions may come about. The modelling of cognition applied in CREAM is model macro-cognition and is based on the **Contextual Control Model** (COCOM, Hollnagel, 1998). *The classification scheme* in CREAM is not a hierarchy of class and subclasses. The highest level of the CREAM classification scheme makes a distinction between effects (phenotypes) and causes (genotypes). The effects (phenotypes) refer to what is observable in the given system.

The causes (genotypes) are the categories to describe which can bring about the effect(s). There are three categories of genotypes: the first category is associated with human psychological characteristics; the second category is associated with the technological system; and the third category is associated with the characteristics of organization, the work environment and the interaction between people.

Instead of the classification scheme, CREAM also provide **Common Performance Conditions (CPCs)** as performance shaping factors (PSFs), and provides a two-level method to calculate Human Error Probability (HEP): the basic method and the extended method (Figure 4.6). Science unpredictable and uncontrolled variability may become part of the causes of incidents and accidents, HRA has naturally been concerned with the variability of human performance. The result of assessing CPCs can be used as the basis for determining the probable genotypes (causes).

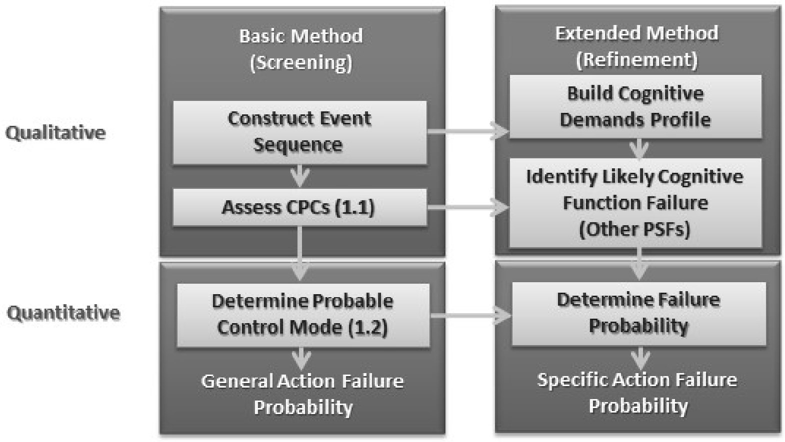


Figure 4.6 CREAM-basic and extended methods (Hollnagel, 1998)

The basic method uses task analysis to identify human actions, and assesses the Common Performance Conditions (CPCs, Table 4.12) by judging the expected effects and making a total or combined score of them with the triplet [$\sum_{\text{reduced}}$, $\sum_{\text{not significant}}$, $\sum_{\text{improved}}$]. Final results are interpreted through the Contextual Control Mode (COCOM) Model: a) *Strategic Control*, the person considers the global context, thus using a wider time horizon and looking ahead at higher level goals. b) *Tactical Control*, performance is based on planning, hence more or less follows a known procedure or rule. c) *Opportunistic Control*, the next action is determined by the salient features of the current context rather than on more stable intentions or goals. d) *Scrambled Control*, the choice of next action is in practice unpredictable or haphazard (Figure 4.7).

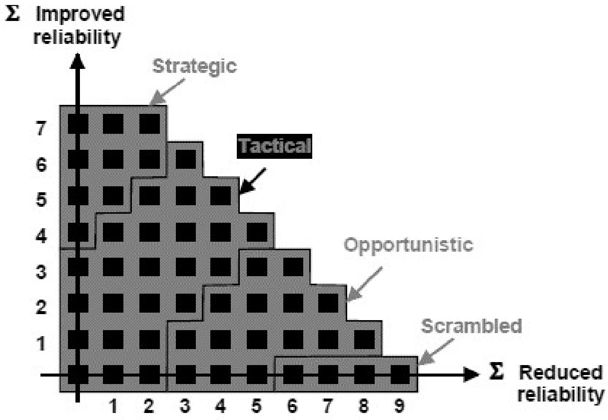


Figure 4.7 Relations between CPC score and control modes (Hollnagel, 1998)

The COCOM model not only defined the control modes, but also provided HEP probability ranges (Table 4.13). If the basic method is not sufficient, CREAM provides the extended method to produce specific action failure probabilities (Hollnagel, 1998).

Table 4.13 Control modes with the logarithm format as Fuzzy output sets (Hollnagel, 1998)

	UOD	Number of Fuzzy Sets	Level/ Descriptors	HEP Ranges	Membership Level Intervals *(Logarithm Format)*
Human Error Probability (HEP)	[0,1]	4	Strategic	$0.5 \times 10^{-5} < P < 1.0 \times 10^{-2}$	-5.3 to -2.3
			Tactical	$1.0 \times 10^{-3} < P < 1.0 \times 10^{-1}$	-3.3 to -1.3
			Opportunistic	$1.0 \times 10^{-2} < P < 0.5$	-2.3 to -0.3
			Scrambled	$1.0 \times 10^{-1} < P < 1.0$	-1.3 to 0

Table 4.12 Common Performance Conditions (Hollnagel, 1998)

CPCs	Level	Effect	Descriptors
Adequacy of Organization	Very Efficient	Improved	The quality of the roles and responsibilities of team members, additional support, communication systems, Safety Management System, instructions and guidelines for externally oriented activities, role of external agencies, etc.
	Efficient	Not significant	
	Inefficient	Reduced	
	Deficient	Reduced	
Working Conditions	Advantageous	Improved	The nature of the physical working conditions such as ambient lighting, glare on screens, noise from alarms, interruptions from the task, etc.
	Compatible	Not significant	
	Incompatible	Reduced	
Adequacy of MMI and Operational Support	Supportive	Improved	The Man-Machine Interface in general, including the information available on control panels, computerised workstations, and operational support provided by specifically designed decision aids.
	Adequate	Not significant	
	Tolerable	Not significant	
	Inappropriate	Reduced	
Availability of Procedures / Plans	Appropriate	Improved	Procedures and plans include operating and emergency procedures, familiar patterns of response heuristics, routines, etc.
	Acceptable	Not significant	
	Inappropriate	Reduced	
Number of Simultaneous Goals	Fewer than capacity	Not significant	The number of tasks a person is required to pursue or attend to at the same time.
	Matching current capacity	Not significant	
	More than capacity	Reduced	
Available Time	Adequate	Improved	The time available to carry out a task and corresponds to how well the task execution is synchronised to the process dynamics.
	Temporarily inadequate	Not significant	
	Continuously inadequate	Reduced	
Time of Day (Circadian Rhythm)	Night-time, (unadjusted)	Reduced	The time of day (or night) describes the time at which the task is carried out, in particular whether or not the person is adjusted to the current time (circadian rhythm). Typical examples are the effects of shift work. It is a well-established fact that the time of day has an effect on the quality of work, and that performance is less efficient if the normal circadian rhythm is disrupted.
	Day-time, (adjusted)	Not significant	
	Night-time, (unadjusted)	Reduced	
Adequacy of Training and Experience	Adequate, High Experience	Improved	The level and quality of training provided to operators as familiarisation to new technology, refreshing old skills, etc. It also refers to the level of operational experience.
	Adequate, Limited Experience	Not significant	
	Inadequate	Reduced	
Crew Collaboration Quality	Very efficient	Improved	The quality of the collaboration between crew members, including the overlap between the official and unofficial structure, the level of trust, and the general social climate among crew members.
	Efficient	Not significant	
	Inefficient	Not significant	
	Deficient	Reduced	

4.2.2.2 FUZZY CREAM

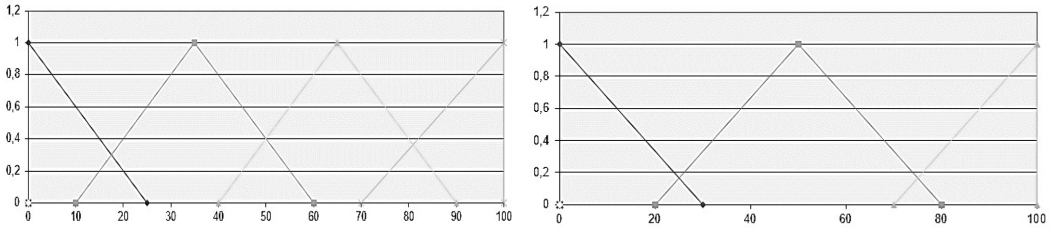
Starting from CREAM basic method, Konstandinidou et al. (2006) introduced FUZZY CREAM as a complementary methodology to assess the HEP. For this study, a dedicated tool was developed to apply FUZZY CREAM, based on both contributions from Konstandinidou et al. (2006) and Monferini et al. (2013). Meanwhile, the Fuzzy Logic Toolbox in Matlab® was used for the result validation.

Step 1 – Fuzzification

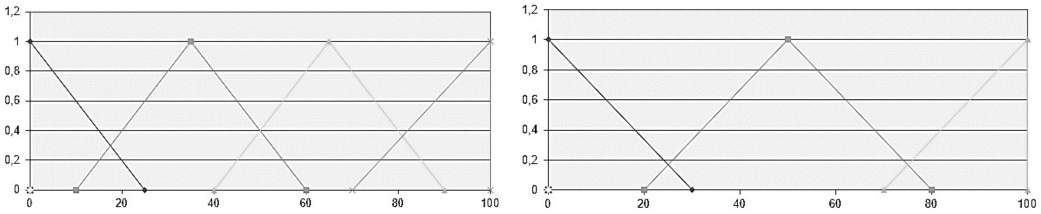
Fuzzy logic starts with the concept of a fuzzy set. In practice, if X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs.

$$A = \{x, \mu_A(x) \mid x X\}$$

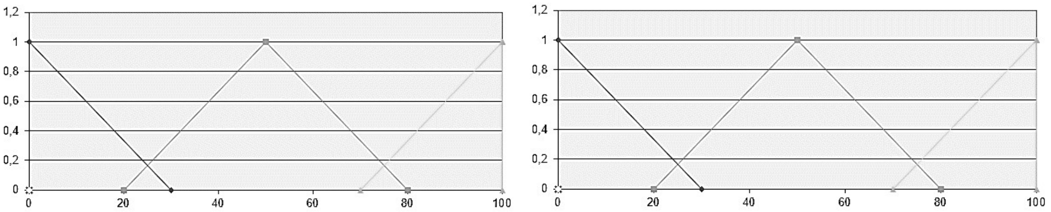
$\mu_A(x)$ is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1. In this FUZZY CREAM tool, triangular membership function was used as straight lines to describe the distributions of each level of a fuzzy input set. The 9 CREAM CPCs mentioned were used to build the input fuzzy sets (Table 4.14 and Figure 4.8) and also the output fuzzy sets were derived from the four control modes provided by COCOM (Table 4.13).



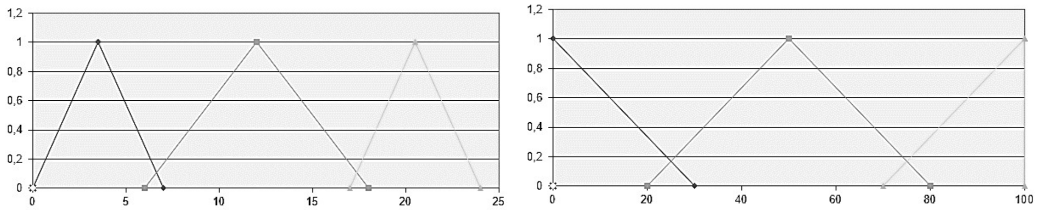
CPC 1. Adequacy of Organization CPC 2. Working Conditions



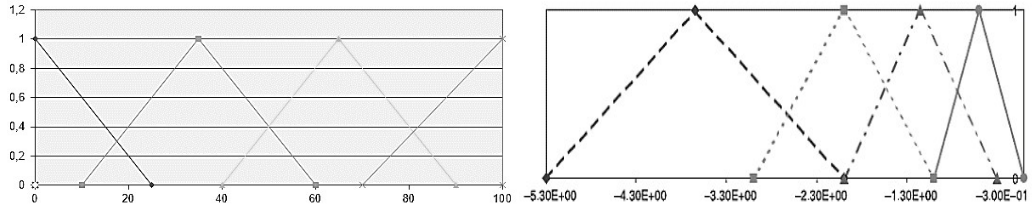
CPC 3. Adequacy of MMI and Operational Support CPC 4. Availability of Procedures/Plans



CPC 5. Number of Simultaneous Goals CPC 6. Available Time



CPC 7. Time of the Day CPC 8. Adequacy of Training and Experience



CPC 9. Crew Collaboration Quality Output: Human Error Probability (Logarithm Format)

Figure 4.8 FUZZY Sets of Nice CPC Inputs and Control Mode Output

Table 4.14 CPCs in CREAM as FUZZY input sets (Konstandinidou et al., 2006, & Monferini et al., 2013)

Inputs		Range	Fuzzy Sets	Level/Descriptors	Effect	Membership Level Intervals	
CPC 1	Adequacy of Organization	[0,100]	4	Very Efficient	Improved	MF1	70-100
				Efficient	Not significant	MF2	40-90
				Inefficient	Reduced	MF3	10-60
				Deficient	Reduced	MF4	0-25
CPC 2	Working Conditions	[0,100]	3	Advantageous	Improved	MF1	70-100
				Compatible	Not significant	MF2	20-80
				Incompatible	Reduced	MF3	0-30
CPC 3	Adequacy of MMI and Operational Support	[0,100]	4	Supportive	Improved	MF1	70-100
				Adequate	Not significant	MF2	40-90
				Tolerable	Not significant	MF3	10-60
				Inappropriate	Reduced	MF4	0-25
CPC 4	Availability of Procedures / Plans	[0,100]	3	Appropriate	Improved	MF1	70-100
				Acceptable	Not significant	MF2	20-80
				Inappropriate	Reduced	MF3	0-30
CPC 5	Number of Simultaneous Goals	[0,100]	3	Fewer than capacity	Not significant	MF1	70-100
				Matching current capacity	Not significant	MF2	20-80
				More than capacity	Reduced	MF3	0-30
CPC 6	Available Time	[0,100]	3	Adequate	Improved	MF1	70-100
				Temporarily inadequate	Not significant	MF2	20-80
				Continuously inadequate	Reduced	MF3	0-30
CPC 7	Time of Day (Circadian Rhythm)	[0,24]	3	Night-time	Reduced	MF1	16-24
				Day-time	Not significant	MF2	8-17
				Night-time	Reduced	MF3	0-9
CPC 8	Adequacy of Training and Experience	[0,100]	3	Adequate, High Experience	Improved	MF1	70-100
				Adequate, Limited Experience	Not significant	MF2	20-80
				Inadequate	Reduced	MF3	0-30
CPC 9	Crew Collaboration Quality	[0,100]	4	Very efficient	Improved	MF1	70-100
				Efficient	Not significant	MF2	40-90
				Inefficient	Not significant	MF3	10-60
				Deficient	Reduced	MF4	0-25

Step 2 - Fuzzy inference

Fuzzy inference is a method that interprets the values in the input vector and, based on some set of rules, assigns values to the output vector. The primary mechanism is doing a list of “if-then” rules. Since in fuzzy logic the truth of any statement is a matter of degree, min-max operations are applied to resolve the statement. In FUZZY CREAM, the rules are constructed in simple linguistic terms and Mamdani's fuzzy inference method is applied. Furthermore, 46656 rules are generated. Here the first rule is presented as an example:

"*IF* Adequacy of Organization is very efficient, *AND*
Working Conditions is advantageous, *AND*
Adequacy of MMI and Operational Support is supportive, *AND*
Availability of Procedures / Plans is appropriate, *AND*
Number of Simultaneous Goals is fewer than capacity, *AND*
Available Time is adequate, *AND*
Time of Day (Circadian Rhythm) is unadjusted Night-time, *AND*
Adequacy of Training and Experience is adequate with high experience, *AND*
Crew Collaboration Quality is very efficient, *THEN*
output is Strategic control mode."

Step 3 – Defuzzification

Defuzzification transforms the final aggregated output fuzzy sets into a single numerical value; the developed FUZZY CREAM tool adopted *Centroid method* for it. The output from Step 2 composes an aggregated area; *Centroid defuzzification* allows to return the center of area under the curve, which is the HEP.

Step 4 -Validation of Results by Matlab®

Fuzzy logic toolbox in Matlab® provides an alternative way to gain HEP from FUZZY CREAM. It was used to validate the result derived from FUZZY CREAM tool application.

4.2.2.3 Application of FUZZY CREAM

FUZZY CREAM tool was applied to the same case study from a food manufacturing company. The dust cartridge filter needs to be regularly replaced, depending on the frequency of use. Lacking or failure of the replacement procedure can cause a dust surplus inside the filter that could break and produce external explosive atmospheres. FUZZY CREAM tool was applied to estimate the Human Error Probability (HEP). The 9 CPCs values were estimated by safety experts and contribute the input vector for FUZZY CREAM application. The HEP output obtained for the case study was 1.58×10^{-2}.

4.2.3 Discussion

The dust cartridge filter case study was firstly subjected to THERP application (Geng et al., 2014), and then to FUZZY CREAM. The improvements led by the second method are hereinafter explained.

4.2.3.1 Performance Shaping Factors (PSF)

THERP identifies Performance Shaping Factors (PSF) that influence HEP, but it doesn't precisely define the rules (only 3 PSFs are involved in the calculation) for their application. On the contrary, CREAM is able to consider technical, human and organizational factors, and it gives very detailed indications on how to treat Common Performance Conditions (CREAM CPCs are the equivalent to THERP PSFs).

4.2.3.2 Application complexity

THERP requires the compiling of many tables, which need a professional background in HOF. The two levels approach provided by CREAM allows users to choose the basic method for HEP calculation, which is very easy to apply. Also, FUZZY CREAM tool can be easily handled by the general safety specialists, after a short training period.

4.2.3.3 Time consuming

HEP calculation in THERP needs more time, because of the tables compiling. On the contrary, the developed FUZZY CREAM tool permits to spare time, because it only requires to safety specialists to assign a judgment to the CPCs; then HEP output is generated by the tool itself.

Chapter 5. Application of the ATEX-HOF Methodology in a Food Industry

Case Study for the Explosive Dust Atmospheres

Chapter Objectives:

5.1 Description of the Case Study

5.2 Step 1: ATEX-HOF Area classification

5.3 Step 2: ATEX-HOF Ignition Source Assessment

5.4 Step 3: ATEX-HOF Damage Analysis

5.5 Step 4: ATEX-HOF Risk Evaluation

5.6 Results for the ATEX-HOF Risk Assessment

Chapter 5. Application of the ATEX-HOF Methodology in a Food Industry

5.1 Description of the Case Study

This case study was original from a food manufacturing plant. The plant produces food stabilizers, ingredients, starches and gums. The traditional ATEX risk assessment identified 44 emission sources; among them, a dust cartridge filter was chosen as a case study, which needs to be replaced regularly, according to the frequency of use mentioned in the maintenance instructions. Lack or failure to replace, dust accumulation inside the filter could break other machines and produce internal and external explosive atmosphere.

5.2 Step 1: ATEX-HOF Area classification

Since the identified flammable substances lead to the explosive dust atmosphere formation, the IEC 60079-10-2 (for dust, 2009) and CEI 31-56 (2007) were applied.

Step 1-1: Identification of Emission Sources

Each item of the process equipment which contains flammable materials is considered as a potential release source.

Table 5.1 Emission sources identification

Emission Sources	Internal Sources of Release	External Sources of Release
A dust cartridge filter	Dust inside the filter	Dust leakage because of the filter replacement during maintenance activities

Step 1-2: Determining the internal zone

The degree of the ventilation was “Low” inside of the filter, and the availability was “Good”. The release grade of the inside clean side was “secondary”; and the release grade of the inside dirty side was “continuous”. Hence, the internal zone was determined (Table 5.2):

Table 5.2 Internal Zone Determination

Emission Sources	Internal Sources of Release	Grade of Release	Ventilation			Internal Zone
			Type	Degree	Availability	
A dust cartridge filter	Dust inside the filter (dirty side)	Continuous	Artificial	Low	Good	Zone 20
	Dust inside the filter (clean side)	Secondary	Artificial	Low	Good	Zone 22

Step 1-3: Determining the external zone

The degree of the ventilation was “Medium” outside of the filter, and the availability was “Good”. The external release grade was “secondary”. **The initial external zone was determined as Zone 22**.

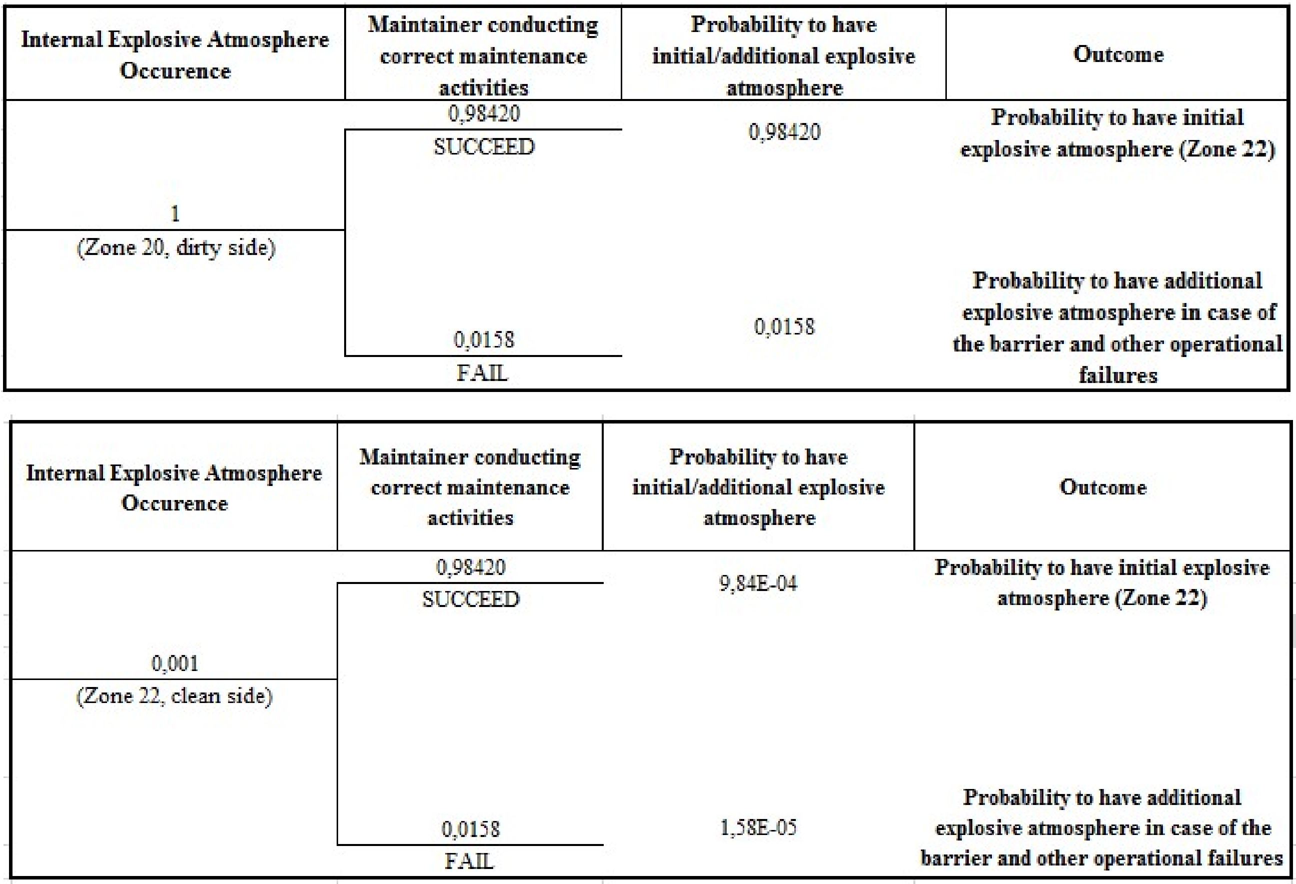
Since the release and the spreading of the flammable substances can be influenced by applied barriers and other human interventions. In the case study, the maintainer conducting the maintenance activities has been considered. The Human Error Probability (HEP) were estimated by applying FUZZY CREAM (Table 5.3):

Table 5.3 HEP estimation

Relevant Human Intervention	CPC 1	CPC 2	CPC 3	CPC 4	CPC 5	CPC 6	CPC 7	CPC 8	CPC 9	HEP
Maintainer	70	65	20	65	25	50	16	60	10	1.58×10^{-2}

The *Event tree* here was built. The initial event has an initial probability (Pr_{IN}) that represents the internal explosive atmosphere occurrence. A series of possible paths are constructed by applied barriers or other relevant operational activities. Each path is assigned with a probability of the failure (Pr_{BF}) or success (Pr_{BS}). The probability allows to calculate the likelihood of having an initial/additional explosive atmosphere.

External Source of Release 1): Dust leakage because of the filter replacement during maintenance activities



Internal Explosive Atmosphere Occurence	Maintainer conducting correct maintenance activities	Probability to have initial/additional explosive atmosphere	Outcome
1 (Zone 20, dirty side)	0,98420 SUCCEED	0,98420	Probability to have initial explosive atmosphere (Zone 22)
	0,0158 FAIL	0,0158	Probability to have additional explosive atmosphere in case of the barrier and other operational failures

Internal Explosive Atmosphere Occurence	Maintainer conducting correct maintenance activities	Probability to have initial/additional explosive atmosphere	Outcome
0,001 (Zone 22, clean side)	0,98420 SUCCEED	9,84E-04	Probability to have initial explosive atmosphere (Zone 22)
	0,0158 FAIL	1,58E-05	Probability to have additional explosive atmosphere in case of the barrier and other operational failures

Figure 5.1 Event tree analysis for the release source – dust leakage

Table 5.4 Final External Zone Determination

Initial External Zone	Probability to have additional explosive atmosphere in case of the operational failure	Final External Zone Determination
0.001 (Zone 22)	1.58E-02 (Zone 21, dirty side)	**Zone 21**
	1.58E-05 (Zone 22, clean side)	

Conclusion: In case of the operational failure (dirty side), the probability to have additional explosive atmosphere generated is higher than the initial external zone. Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional explosive atmosphere. The most influential failure is result from maintainer's activities.

Step 1-4: Results of the ATEX-HOF Area classification

Table 5.5 shows the area classification results from both internal and external sides of the dust cartridge filter. Further, with the sum of all external zones, the envelop of the external zones were drawn on the layout to understand the critical area. The final analysis was completed.

Table 5.5 ATEX-HOF Area classification result

Emission Source	**Internal Source of Release**	**Grade of Release**	**Internal Zone**	**Pr_{IN}**	**External Source of Release**	**Grade of Release**	**Relevant Operational Activities and/or Applied Barriers**	**Initial External Zone** (without human intervention and barrier failures)	**PSA** (Probability to have additional explosive atmosphere)	**External Zone**
A dust cartridge filter	Dust inside the filter (dirty side)	Continuous	**Zone 20**	1 (365 days operations)	Dust leakage because of the filter replacement during maintenance activities	Secondary	Maintainer conducting correct maintenance activities	Zone 22	1.58×10^{-2}	**Zone 21**
	Dust inside the filter (clean side)	Secondary	**Zone 22**	0,001					1.58×10^{-5}	

5.3 Step 2: ATEX-HOF Ignition Source Assessment

Ignition source assessment is the second step to go through if the zone classification is determined as dangerous zone. Potential ignition sources are identified based on 13 possible ignition sources listed in EN 1127-1 (Table 4.4). Once the presence of the ignition source is identified, the frequency of occurrence will be assessed (EN 13463-1, 2009): 1) occurrence *during normal operation*; 2) occurrence *during foreseeable malfunction*; 3) occurrence *during rare malfunction*; 4) *not relevant*.

It is known that one has to supply initial ignition energy to initiate combustion process. A flammable mixture air can be ignited by an external source of energy such as electric spark, a naked flame, hot vessel walls, etc. It is possible to ignite any flammable mixture only when the maximum generated energy is enough to ignite the mixture (above the minimum ignition energy, MIE).

In case that identified potential ignition source is effective, applied barriers and relevant human interventions should be considered. The Event tree has been built. There is one technical barrier applied: the ground system. As the provided technical document: $\underline{P_{tbf} = 3.83\times10^{-4}}$. The relevant operational activities are conducted by the maintainer. According to the general working context and the personal working performances, the HEP were estimated by applying FUZZY CREAM: HEP (maintainer) =$\underline{1.58\times10^{-2}}$. Therefore, the ignition source assessment (during conducting the replacement relevant maintenance activities) were conducted. The final ignition likelihood is assessed in the conservative way. The maximum value of the ignition likelihood among all identified potential ignition sources will be chosen as the final result.

Table 5.6 ATEX-HOF Ignition source assessment **(Internal assessment result**: **Rarely)**

1-Presence of potential ignition sources					**2-Effectiveness**	**3-Final ignition likelihood**			
Potential ignition sources		**Motivation for assessment**	**Frequency of occurrence (without applied barriers)**	**Initial Ignition Likelihood P_{IG} (without applied barriers)**		**Barriers applied**	**Probability to have additional ignition likelihood**	**Frequency of Occurrence (including applied barriers)**	**Final Ignition Likelihood**
Internal Ignition Sources	Hot Surface	The temperature inside and outside of the equipment is less than the auto ignition temperature of flammable substances.	Not Relevant	--	N	--	--	--	N.E.
	Mechanical Sparks	Mechanical sparks may be generated from the use of improper manual tools during the maintenance activities.	During rare malfunction	1×10^{-3}	Y	The maintenance is performed under the safety requirements and the procedures.	1.58×10^{-5}	During rare malfunction	Rarely
	Static Electricity	Parts of non-metallic material are present. With received technical documentation, the materials are made of antistatic material.	Not relevant	--	N	--	--	--	N.E.
		The use of metallic materials may potentially cause disruptive discharges.	During normal operation	1	Y	1) Bond all conductors together and to earth. (technical barrier) 2) Periodic checking of the earth situation with taking into account of specific procedures.	6.051×10^{-6}	Not relevant	N.E.

Table 5.7 ATEX-HOF Ignition source assessment **(External assessment result: Rarely)**

1-Presence of potential ignition sources				**2-Effectiveness**	**3-Final ignition likelihood**			
Potential ignition sources	**Motivation for assessment**	**Frequency of occurrence (without applied barriers)**	**Initial Ignition Likelihood P_{IG} (without applied barriers)**		**Barriers applied**	**Probability to have additional ignition likelihood**	**Frequency of Occurrence (including applied barriers)**	**Final Ignition Likelihood**
Hot Surface	Electrical equipment may generate hot surface in case of failure. However, the temperature inside and outside of the equipment is less than the auto ignition temperature of flammable substances.	Not Relevant	--	N	--	--	--	N.E.
Mechanical Sparks	Mechanical sparks may be generated externally from the use of improper manual tools during the maintenance activities.	During rarely malfunction	1×10^{-3}	Y	Maintainer from outside the paint mixing room is performing the maintenance with the safety requirement and following the procedure, e.g. always choose the ATEX required manual tools. (maintainer)	1.58×10^{-5}	During rare malfunction	Rarely
Electrical Sparks	ATEX required electrical equipment are applied so that it is impossible to be effective even in case of failure.	Not relevant	--	N	--	--	--	N.E.
Static Electricity	The use of metallic materials may potentially cause disruptive discharges.	During the normal operation	1	Y	1) Bond all conductors together and to earth. (technical barrier) 2) Periodic checking of the earth situation with taking into account of specific procedures.	6.051×10^{-6}	Not relevant	N.E.
	Parts of non-metallic material are present. With received technical documentation, the materials are made of antistatic material.	Not relevant	--	N	--	--	--	N.E.
	Persons who are insulated from earth can easily acquire and retain an electrostatic charge. However, since the work equipment, during normal operation and in case of failure, cannot give rise to incendive discharges in hazardous areas, static electricity is not possible generated by person.	Not relevant	--	N	--	--	--	N.E.

5.4 Step 3: ATEX-HOF Damage Analysis

ATEX-HOF damage analysis relies on the Area classification result and other factors. Given to the guidance of the ATEX risk assessment application (Cavaliere and Scardamaglia, 2005; and Cavaliere, 2011), the formulas and indexes support the calculation of the semi-quantitative parameter D_{HOF}. If the zone prediction changes in the ATEX-HOF Area classification, the ID value is also changed as ID_{HOF}.

$$D_{HOF} = ID_{HOF} + PL + KST + VZ + SS + CN \text{ (for dust)} \qquad \text{Eq. (5.1)}$$

5.5 Step 4: ATEX-HOF Risk Evaluation

According to Table 4.9 of Chapter 4, the values of P_{HOF}, C_{HOF}, and D_{HOF} can be determined through the results from Step 1 to Step 3. The ATEX-HOF risk (R_{HOF}) was the multiplication of P_{HOF}, C_{HOF}, and D_{HOF} ($R_{HOF} = P_{HOF}\times C_{HOF}\times D_{HOF}$), and the final risk level can be ranked.

Table 5.8 Traditional ATEX Risk evaluation result for the basic paint mixing unit
(in case of relevant operational activities and applied barriers **success**)

Emission Source	**Area Classification**	**P**	**Effectiveness of Ignition Source**	**C**	**D**	**R = P×C×D**	**Risk Level**
A dust cartridge filter	Dust inside the filter (dirty side)	3	Internal: Not relevant	0	3.6	R<1	Negligible
	Dust inside the filter (clean side)	1	External: Not relevant	0	1.2	R<1	Negligible
	External (leakage)	1		0	1.2	R<1	Negligible

Table 5.9 Traditional ATEX Risk evaluation result for the basic paint mixing unit
(in case of relevant operational activities and applied barriers **failure**)

Emission Source	**Area Classification**	**P_{HOF}**	**Effectiveness of Ignition Source**	**C_{HOF}**	**D_{HOF}**	**$R_{HOF} = P_{HOF}\times C_{HOF}\times D_{HOF}$**	**Risk Level**
A dust cartridge filter	Dust inside the filter (dirty side)	3	Internal: Rarely	1	3.6	10.8	Medium
	Dust inside the filter (clean side)	1	External: Rarely	1	1.2	1.2	Low
	External (leakage)	2		1	2.4	4.8	Low

5.6 Results for the ATEX-HOF Risk Assessment

As mentioned above, the risk level of the basic paint mixing unit is NEGLIGIBLE for the dust cartridge filter (internal and external sides) in case of the maintainer conducting the correct replacement relevant maintenance activities.

In case of fail to conduct the replacement relevant maintenance activities, the risk level goes up to the MEDIUM level inside the dirty side; and LOW level inside the clean side of the dust cartridge filter and the same as the outside of the filter. Risk mitigation measures should be implemented according to the Table 5.10.

Table 5.10 ATEX-HOF Risk Evaluation Criteria

Value (RHOF)	Risk Level	Description	Risk Control
$\mathrm{RHOF} \geq 18$	High	High likelihood of presence of explosive atmosphere. Ignition sources are present and effective. Consequences of an explosion are extermely serious. Likelihood of explosion propagation is very high.	Risk mitigation measures must be implemented.
$9 \leq \mathrm{RHOF} < 18$	Medium	Likely presence of explosion atmosphere and ignition sources can be present and effective. In case of an explosions, consequences are moderate with marginal damage to personnel and process units. Explosion propagation is likely to be moderate.	Risk mitigation measures should be implemented in a short time interval.
$1 \leq \mathrm{RHOF} < 9$	Low	The likelihood of presence of an explosive atmosphere is extremely limited, as well as the presence of effective ignition sources. The exposure level is low, so with limited damage to persons and property. The probability of propagation of the explosion is to be considered extremely limited.	Risk mitigation measures should be implemented in a long time interval.
$\mathrm{RHOF} \leq 1$	Negligible	Likelihood of explosion atmosphere presence is very unlikely or ignition sources are not present or they are not effective. There are not consequences to personnel or equipment. Explosion propagation is very unlikely to occur.	Operations should be kept monitoring in order to control the risk in this level.

Chapter 6. Application of the ATEX-HOF Methodology in an Automotive Manufacturing Industry

Case Study for the Explosive Gas Atmospheres

Chapter Objectives:

6.1 Description of the Case Study

6.2 Step 1: ATEX-HOF Area Classification

6.3 Step 2: ATEX-HOF Ignition Source Assessment

6.4 Step 3: ATEX-HOF Damage Analysis

6.5 Step 4: ATEX-HOF Risk Evaluation

6.6 Results for the ATEX-HOF Risk Assessment

Chapter 6. Application of the ATEX-HOF Methodology in an Automotive Manufacturing Industry

ATEX (explosive atmosphere) risk assessment is required when any equipment or system potentially cause explosive atmospheres. Cavaliere and Scardamaglia (2005) and Cavaliere (2011) provided a methodology for the ATEX risk assessment that fulfills the requirements of both ATEX Directive 94/9/EC and related standards. However, when reviewing the ATEX risk assessment procedures, despite many operations on plant and equipment containing dangerous substances are performed by operators, the influence of human and organizational factors (HOF) are neglected (e.g. maintenance activity). The ATEX-HOF methodology is proposed based on the traditional methodology, with the aim of providing an advanced methodology to analyze HOF influences on ATEX hazards.

In Chapter 5, a case study that deals with explosive dust atmospheres was applied. In Chapter 6, another case study under the explosive gas atmospheres situation is applied, in order to investigate the applicability of the ATEX-HOF Methodology in various industrial environment.

6.1 Description of the Case Study

The case study was originally taken from the Central paint mixing station in an automotive manufacturing plant. Paint application is one of the most important automobile manufacturing processes. Not only does the paint coating protect the body surface, it also enhances visual appeal. For the use of primer, coat, paints, and solvents, materials contain flammable substances that potentially cause risks to have explosive gas atmospheres. Ten groups of emission sources were identified which were separated in different rooms of the Central paint mixing station: Storage room, Solvent mixing room, and Paint mixing room. Inside the paint mixing room, **the basic paint mixing unit** (Figure 6.1) was selected as a case study to apply the ATEX-HOF methodology.

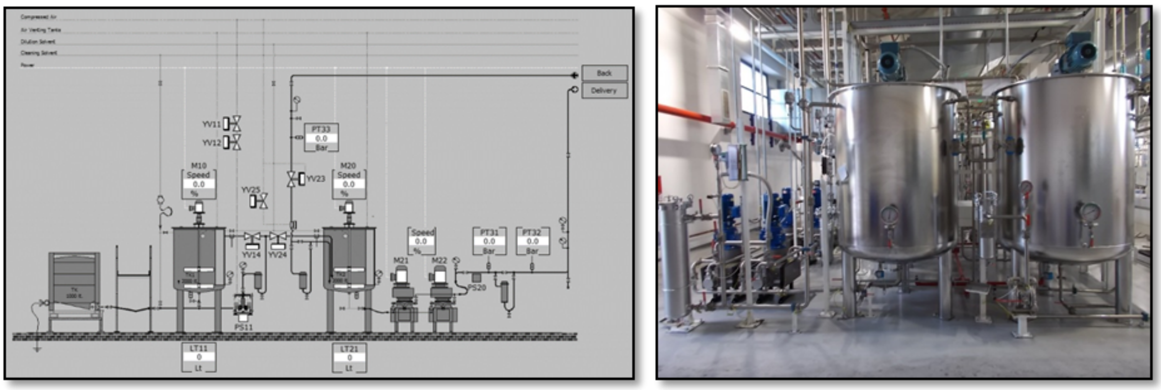


Figure 6.1 Layout and the Photo of One Paint Mixing Unit

Operation Principles:

The basic paint mixing unit has a double tank for the preparation and pumping high consumption paint. The 1000 lt container with the product provided by the supplier of the product is positioned on the relative support close to the group. The flexible suction tube is connected and, through use of the transfer pump, the product is transferred to the preparation tank.

In the preparation tank it is adequately diluted by adding dilution solvent, checking the quantity using the manual litre counter. The product is mixed using the electric shaker fitted on the cover. The product created in this way is transferred to the working tank through the membrane pump for transfer, therefore making the preparation tank ready for a new preparation cycle. The electric pump powers the distribution circuit keeping the product in re-circulation. The pressure in the re-circulation circuit is controlled and maintained by means of a return regulator. A signal generated by the supervision system informs the operator that the minimum level set in the working tank that manually operates on the valves to select the circuit that allows the transfer pump to transfer the product from the preparation tank to the working tank, has been reached.

The management group and the loading of products is completely manual. The operator is responsible for controlling these operations acting on the panel of selectors and the QP control flow meter.

The station is staffed by three daily shifts. Each shift (8 hours per day) mainly has one shift leader, two operators, and one daily maintainer. Paint mixing operation is 365-day operation. Paint mixing operation is one-by-one operation. Two simultaneous mixing operations are prohibited.

6.2 Step 1: ATEX-HOF Area Classification

The ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures. Inside the basic paint mixing unit, there are different flammable substances in a mixture. As reported the results are those related to more critical substances, the explosive gas atmosphere may be potentially caused by flammable liquid, gas and vapours. The general procedures mainly refers to the standard IEC 60079-10-1 (2010) the Italian guideline CEI 31-35 (2012), which are summarized as:

- Step 1-1: General on-site information, flammable substance and emission source identification
- Step 1-2: Determining the area classification inside the equipment
- Step 1-3: Determining the area classification outside the equipment
- Step 1-4: Area classification results

Step 1-1: General information, flammable substances, and source of release identification

The general on-site information:

Location: Indoor Situation
Ventilation Condition: General Artificial Ventilation (GAV)
Atmospheric Pressure: 1013 mbar
Maximum Outdoor Temperature in summer: 35°C
Maximum Indoor Temperature: 21-25°C
Total Max Air Flow: 120000 (m^3/h)
The Area of the Building: 1123.61 (m^2)
The Building Size (V_0): 6685.48 (m^3)

The critical flammable substances from each collected safety data sheet (applied paints) are identified in Table 6.1.

Table 6.1 Important Parameters of the Identified Flammable Substances

Composition	Flash Point (°C)	LEL		Molar Mass M (kg/kmol)	Coefficience of diffusion c_d	Vapour Pressure at 20°C, P_v (Pa)	Density of Liquid ρ_{liq} (kg/m^3)	Relative Density Gas/Air	Auto Ignition Temp. (°C)	Temprature Class	Equipment Group
		g/m^3	vol. %								
naphtha	<0	--	1,1	114	0,060	827	760	--	--	--	--
butanone	-10	45	1,8	72,1	0,031	1058	800	2,48	404	T2	IIA
heptane	-7	35	0,85	100,2	0,025	10653	684	3,46	204	T3	IIA
toluene	4	39	1,1	92,14	0,028	1830	866	3,18	480	T1	IIA
propan-2-ol	12	50	2	60,09	0,036	4201	789	2,1	400	T2	IIA
ethylbenzene	15	44	0,8	106,17	0,024	931	867	3,66	431	T2	IIA
4-methylpentan-2-one	16	50	1,2	100,2	0,026	2128	802	3,45	475	T1	IIA
n-butyl acetate	22	58	1,7	116,16	0,024	1064	882	4,01	390	T2	IIA
2-methylpropan-1-ol	28	43	1,4	74,12	0,031	1232	805	2,55	408	T2	IIA

Each item of the process equipment which contains flammable materials is considered as a potential release source. Table 6.2 summarizes identified emission sources.

Table 6.2 Emission sources identification for the basic paint mixing unit

Emission Sources		Quantity	Internal Sources of Release	External Sources of Release
Paint Loading Container	1000L. Paint Loading Container	1	Liquid surface within the paint loading container	1) Openings in the loading container; 2) Leakage of liquid close to the loading container.
Fixed Process Mixing Vessels	2000 L. Fixed Process Mixing Vessel	2	Liquid surface within the mixing vessel	1) Vent openings and other openings in the mixing vessel. 2) Spillage or leakage of liquid close to the mixing vessel.
Supply System	Filter S.S. 20”	1	Liquid surface within the supply system	1) Structural emission from connectors and gaskets. 2) Leakage from seals, flanges, pipe fittings, and other connectors in case of failure.
	Filter S.S. PN-16 10”	2		
	Electric Pump	2		
	Pneumatic Diaphragm Pump	1		
	Valves	62		
	Hoses	3		

Step 1-2: Determining the area classification inside the equipment

The type of the area classification inside the equipment (the internal zone) can be referred to the grade of release and the ventilation conditions. It is generally conducted in a qualitative way. Three levels of the grade of releases are mentioned in IEC 60079-10-1 (2008): 1) *a continuous grade of release*, 2) *a primary grade of release*, and 3) *a secondary grade of release.* Further, the flammable substances released into the atmosphere can be diluted by dispersion or diffusion into the air until its concentration is below the Lower Explosive Limit (LEL). Ventilation helps promoting dispersion, and Table 4.1 shows the influence of the ventilation on determining the type of zone. The effectiveness of the ventilation will depend upon the degree (High, Medium, Low) and availability (Good, Fair, Poor) of ventilation and the design of the system. Hence, the internal zone for each identified emission source was determined (Table 6.3):

Table 6.3 Internal Zone Determination for the Basic Paint Mixing Unit

Emission Sources		**Quantity**	**Internal Sources of Release**	**Grade of Release**	**Ventilation**			**Internal Zone**
					Type	**Degree**	**Availab ility**	
1000L. Paint Loading Container		1	Liquid surface within the paint loading container	Continuous	Artificial	Low	Poor	Zone 0
2000 L. Fixed Process Mixing Vessel		2	Liquid surface within the mixing vessel	Continuous	Artificial	Low	Good	Zone 0
Supply System	Filter S.S. 20”	1	Liquid surface within the supply system	Continuous	Artificial	Low	Good	Zone 0
	Filter S.S. PN-16 10”	2						
	Electric Pump	2						
	Pneumatic Diaphragm Pump	1						
	Valves	62						
	Hoses	3						

Step 1-3: Determining the area classification outside the equipment

1) Initial External Zone Determination

Determining the area classification outside the equipment (the external zone) is based on the release rate, LEL, ventilation and other factors (e.g. climatic conditions, etc.). The external zone depends on the estimated area over which the explosive atmosphere insists before it disperses.

The ventilation condition is relied on the type, degree, and availability of the ventilation. In the central paint mixing station, the type of the ventilation is the general artificial ventilation. The degree is estimated by calculating the hypothetical volume V_z with Formula B4 and Formula B3 (Annex B.5.2.2 CEI EN 60079-10-1, Indoor situation):

$$Vz = f * Vk = \frac{f * \left(\frac{dV}{dt}\right) min}{C} \qquad C = \frac{\left(\frac{dV_0}{dt}\right)}{V_0}$$

where,

- V_z: Hypothetical volume of potentially explosive atmosphere including safety coefficient k (m^3);
- f: Efficiency of ventilation in terms of its effectiveness in diluting the explosive gas atmosphere, whit f ranging from f=1 (ideal solution) to, typically f=5 (impeded air flow);
- V_k: Hypothetical volume of potentially explosive atmosphere in the presumption of an instantaneous and homogeneous mixture with air near the source, under ideal conditions the fresh air flow (f = 1) (m^3);
- $(dV/dt)_{min}$ is the minimum volumetric flow rate of fresh air (volume per time, m^3/s);
- C: Number of fresh air changes per unit time (s^{-1});
- (dV_0/dt): Total flow rate of fresh air through the volume under consideration;
- V_0: Entire volume (within the control of the plant) served by actual ventilation in the vicinity of release being considered.

To ascertain the hypothetical volume V_z, it is necessary to first establish the theoretical minimum ventilation flow rate of fresh air $\mathbf{(dV/dt)_{min}}$ to dilute a given release of flammable material to the required concentration below the lower explosive limit. This can be calculated by means of the Formula B1 (Annex B.5.2.2 CEI EN 60079-10-1):

$$\left(\frac{dV}{dt}\right) min = \frac{\left(\frac{dG}{dt}\right) max}{k * LELm} * \frac{T}{293}$$

where,

- $(dV/dt)_{min}$ is the minimum volumetric flow rate of fresh air (volume per time, m^3/s);
- $(dG/dt)_{max}$ is the maximum rate of release at source (mass per time, kg/s);
- LEL_m is the lower explosive limit (mass per volume, kg/m^3);
- k is a safety factor applied to the LEL_m; typically:
  k = 0,25 (continuous and primary grades of release)
  k = 0,5 (secondary grades of release);
- T is the ambient temperature (in Kelvin, K).

As a result, given to the calculation of the hypothetical volume V_Z and other parameters, the ventilation conditions are determined. With the identified grade of release and the ventilation condition, the initial external zone for each emission source was determined (Table 6.4). Figure 6.2 shows an example of the way to determine the external zone via the event tree.

Table6.4 Initial External Zone Determination for the Basic Paint Mixing Unit

Emission Sources		Quantity	External Sources of Release	Grade of Release	Ventilation			Initial External Zone
					Type	Degree	Availability	
1000L. Paint Loading Container		1	1) Openings in the loading container;	Primary	Artificial	Medium	Good	Zone 1
			2) Leakage of liquid close to the loading container.	Secondary	Artificial	Medium	Good	Zone 2
2000 L. Fixed Process Mixing Vessel		2	1) Vent openings and other openings in the mixing vessel.	Primary	Artificial	Medium	Good	Zone 1
			2) Spillage or leakage of liquid close to the mixing vessel.	Secondary	Artificial	Medium	Good	Zone 2
Supply System	Filter S.S. 20”	1	1) Structural emission from connectors and gaskets.	Primary	Artificial	Medium	Good	Zone 1
	Filter S.S. PN-16 10”	2						
	Electric Pump	2						
	Pneumatic Diaphragm Pump	1	2) Leakage from seals, flanges, pipe fittings, and other connectors in case of failure.	Secondary	Artificial	Medium	Good	Zone 2
	Valves	62						
	Hoses	3						

2) Calculation: Failure Probability of Applied Barriers and/or other Operational Activities

The release and the spreading of the flammable substances can be influenced by applied barriers (technical barriers, e.g. grounding system; operational barriers, e.g. maintaining activities), and other human interventions. In the case study, the operational barriers and other relevant operational activities are conducted by two people: a) one is the operator performing daily tasks in a normal operation condition (Scenario 1); and b) another is the maintainer conducting the maintenance activities (Scenario 2). The Human Error Probability (HEP) were estimated (Table 6.5):

Table 6.5 HEP estimation for scenario 1 (sc.1) and scenario 2 (sc.2) by applying FUZZY CREAM

Sc.	CPC 1	CPC 2	CPC 3	CPC 4	CPC 5	CPC 6	CPC 7	CPC 8	CPC 9	HEP
Sc. 1	80	70	70	80	70	70	14	75	70	5.01×10^{-3}
Sc. 2	70	65	20	65	25	50	16	60	10	1.58×10^{-2}

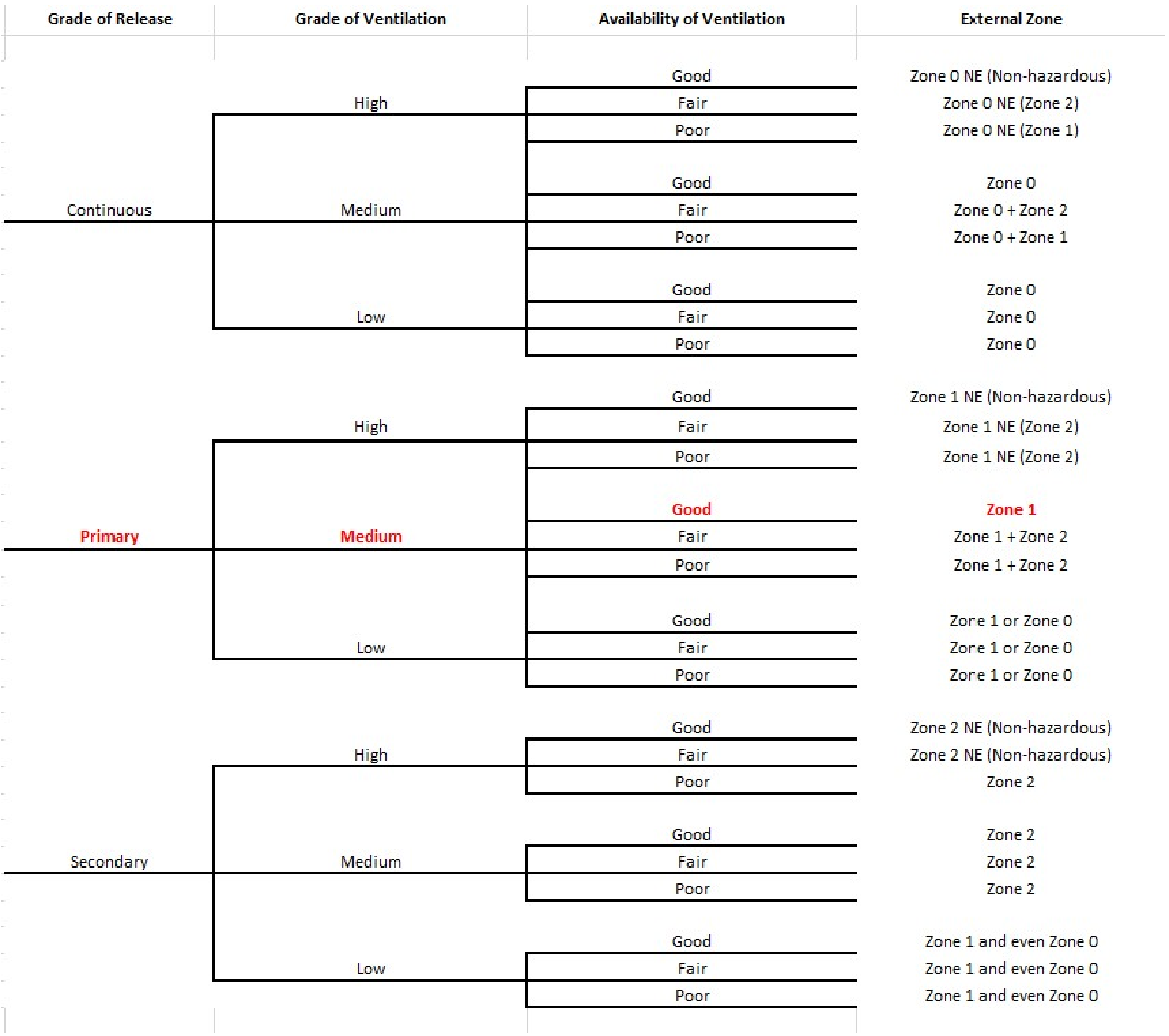


Figure 6.2 Example of Initial External Zone Determination – Openings in the fixed mixing vessel

3) Event tree analysis and the Final External Zone Determination

The *Event tree* (Papazoglou, 1998) is here introduced for a *probabilistic safety assessment (PSA)*. The initial event has an initial probability (Pr_{IN}) that represents the internal explosive atmosphere occurrence. A series of possible paths are constructed by applied barriers or other relevant operational activities. Each path is assigned with a probability of the failure (Pr_{BF}) or success (Pr_{BS}). The probability allows to calculate the likelihood of having an initial/additional explosive atmosphere.

External Source of Release 1): Openings in the loading container

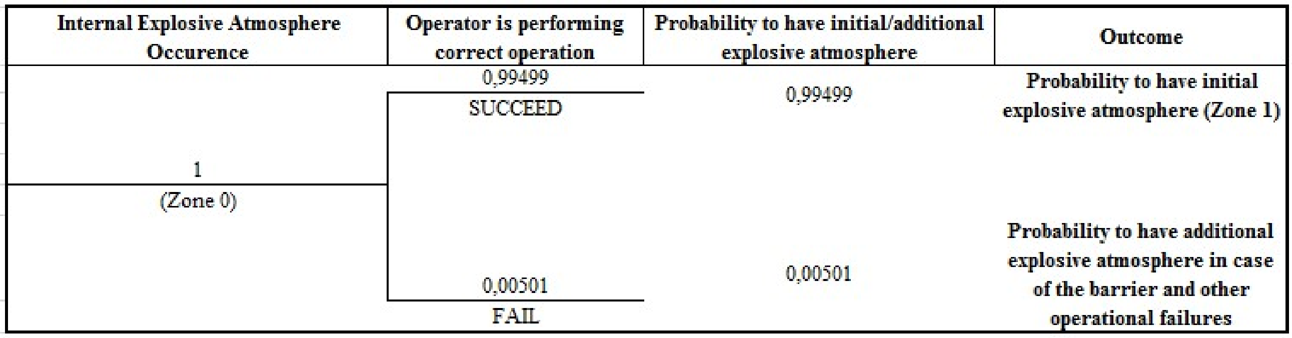


Figure 6.3 Event tree analysis for the release source – opening in the loading container

Table 6.6 Final External Zone Determination

Initial External Zone	Probability to have additional explosive atmosphere in case of the operational failure	**Final External Zone Determination**
0,1 (Zone 1)	5,010E-03 (Zone 1)	**Zone 1**

Conclusion: Even in case of the relevant operational failure, the probability to have additional explosive atmosphere generated is less than (or within the range of) the initial external zone (Table 6.6). Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial external zone.

External Source of Release 2): Openings in the fixed mixing vessel

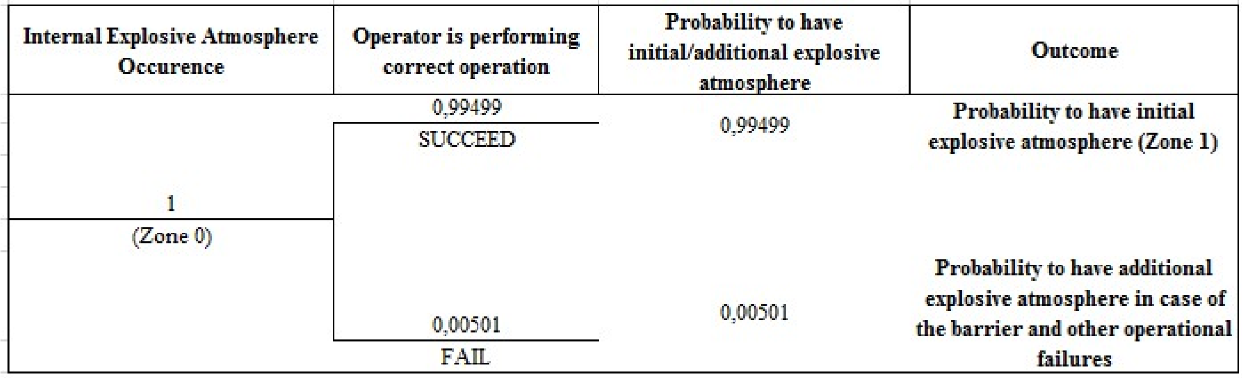


Figure 6.4 Event tree analysis for the release source – openings in the fixed mixing vessel

Table 6.7 Final External Zone Determination

Initial External Zone	Probability to have additional explosive atmosphere in case of the operational failure	**Final External Zone Determination**
0,1 (Zone 1)	5,010E-03 (Zone 1)	**Zone 1**

Conclusion: Even in case of the relevant operational failure, the probability to have additional explosive atmosphere generated is less than (or within the range of) the initial external zone (Table 6.7). Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial external zone.

<u>External Source of Release 3):</u> Structural Emission from the Supply System

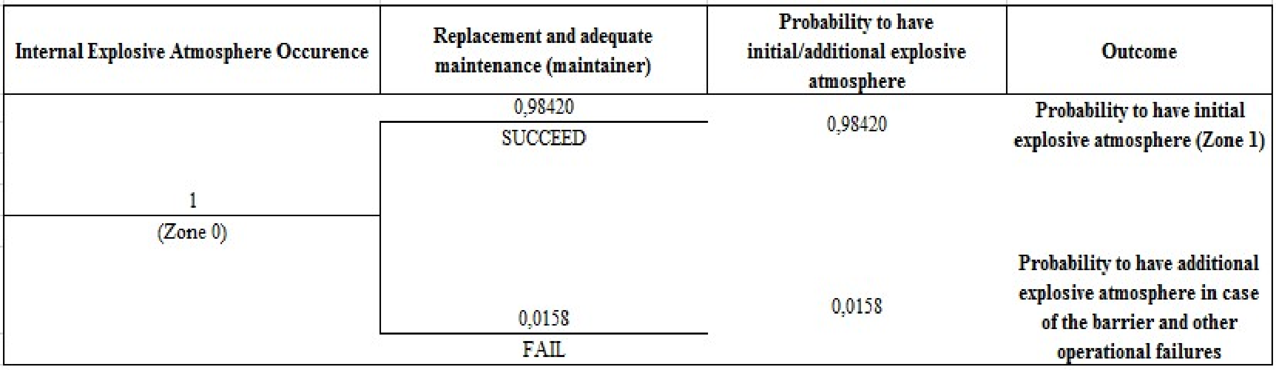


Figure 6.5 Event tree analysis for the release source – Structural emission from the supply system

Table 6.8 Final External Zone Determination

Initial External Zone	**Probability to have additional explosive atmosphere in case of the operational failure**	**Final External Zone Determination**
0,1 (Zone 1)	1,580E-02 (Zone 1)	**Zone 1**

Conclusion: Even in case of the relevant operational failure, the probability to have additional explosive atmosphere generated is less than (or within the range of) the initial external zone (Table 6.8). Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial external zone.

<u>External Source of Release 4):</u> Spillage, Leakage in case of Failure (for the paint loading container)

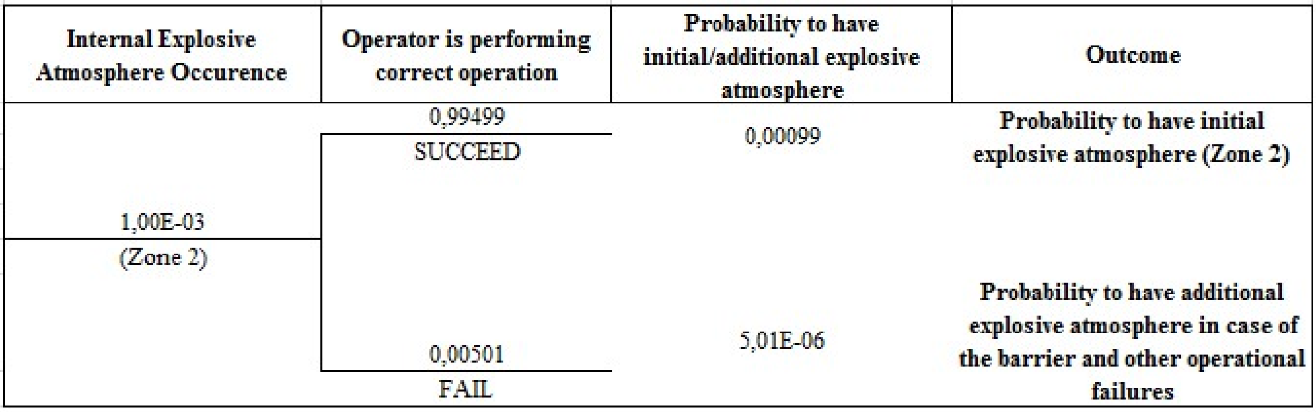


Figure 6.6 Event tree analysis for the release source – Spillage, leakage in case of failure

Table 6.9 Final External Zone Determination

Initial External Zone	Probability to have additional explosive atmosphere in case of the operational failure	**Final External Zone Determination**
0,001 (Zone 2)	5,01E-06 (Zone N.E.)	**Zone 2**

Conclusion: Even in case of the relevant operational failure, the probability to have additional explosive atmosphere generated is less than (or within the range of) the initial external zone (Table 6.9). Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial external zone.

External Source of Release 5): Spillage, Leakage in case of Failure (for the mixing vessel and the supply system)

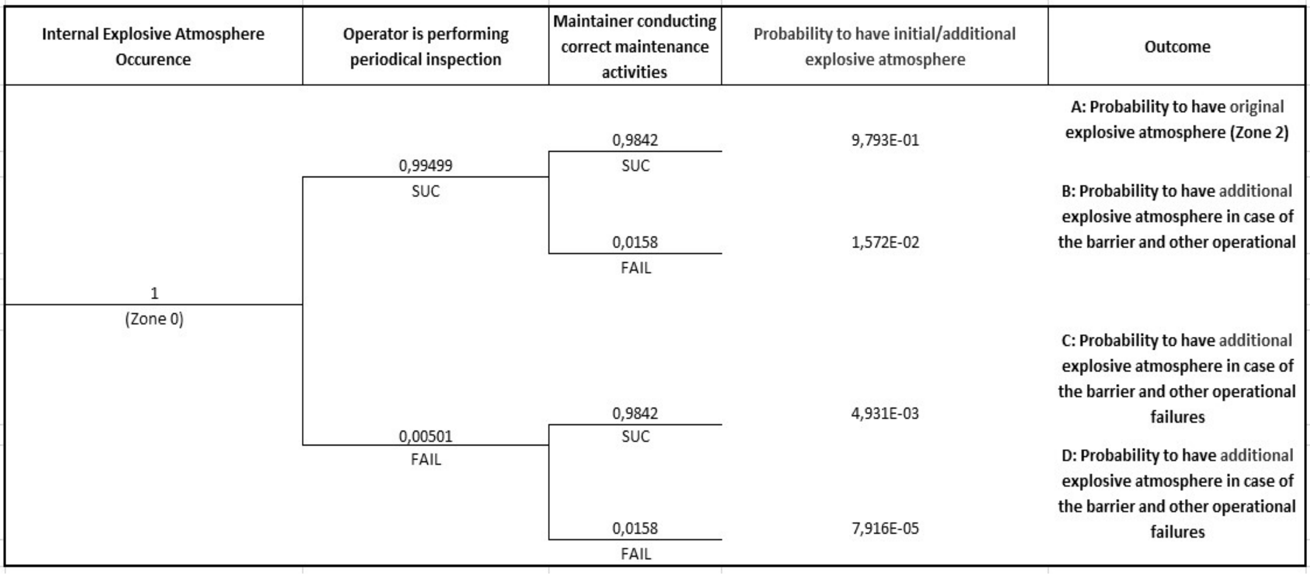


Figure 6.7 Event tree analysis for the release source – Spillage, leakage in case of failure

Table 6.10 Final External Zone Determination

Initial External Zone	Probability to have additional explosive atmosphere in case of the operational failure (B+C+D)	**Final External Zone Determination**
0,001 (Zone 2)	2,073E-02 (Zone 1)	**Zone 1**

Conclusion: In case of barrier failure and other operational failure, the probability to have additional explosive atmosphere generated is higher than the initial external zone. Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional explosive atmosphere. The most influential failure is result from maintainer's activities.

Step 1-4: Results of the ATEX-HOF Area classification

Table 6.11 shows the area classification result from both internal and external sides of the basic paint mixing unit. Further, with the sum of all external zones, the envelop of the external zones were drawn on the layout to understand the critical area (Figure 6.8). The final analysis was completed.

Table 6.11 ATEX-HOF Area classification result for the basic paint mixing unit

Emission Source	**Internal Source of Release**	**Grade of Release**	**Internal Zone**	**Pr_{IN}**	**External Source of Release**	**Grade of Release**	**Relevant Operational Activities and/or Applied Barriers**	**Initial External Zone** (without human intervention and barrier failures)	**PSA** (Probability to have additional explosive atmosphere)	**External Zone**
The paint loading container (1000L.)	Liquid surface within the loading container	Continuous	**Zone 0**	1 (365 days operations)	Openings in the paint loading container	Primary	*Relevant Operation 1:* Operator is correctly checking and monitoring parameters by following designed procedures.	Zone 1	5.01×10^{-3}	**Zone 1**
					Leakage of liquid close to the paint loading container.	Secondary	*Relevant Operation 1:* Operator is performing periodical inspection.	Zone 2	5.01×10^{-6}	**Zone 2**
The fixed process mixing vessel (2000L.)	Liquid surface within the mixing vessel	Continuous	**Zone 0**	1 (365 days operations)	Vent openings and other openings in the mixing vessel.	Primary	*Relevant Operation 1:* Operator is correctly checking and monitoring parameters by following designed procedures.	Zone 1	5.01×10^{-3}	**Zone 1**
					Spillage or leakage of liquid close to the mixing vessel.	Secondary	*Relevant Operation 1:* Operator is performing periodical inspection *Relevant Operation 1:* Any performed maintenance work follows procedures, e.g. replacement of grate guard, and cleaning activities.	Zone 2	2.073×10^{-2}	**Zone 1**
Supply system	Liquid surface within the supply system	Continuous	**Zone 0**	1 (365 days operations)	Structural emission from connectors and gaskets.	Primary	*Relevant Operation 1:* Replacement and adequate maintenance. (maintainer)	Zone 1	1.58×10^{-2}	**Zone 1**
					Leakage from seals, flanges, pipe fittings, and other connectors in case of failure.	Secondary	*Relevant Operation 1:* Operator is performing periodical inspection *Relevant Operation 1:* Replacement and adequate maintenance.	Zone 2	2.073×10^{-2}	**Zone 1**

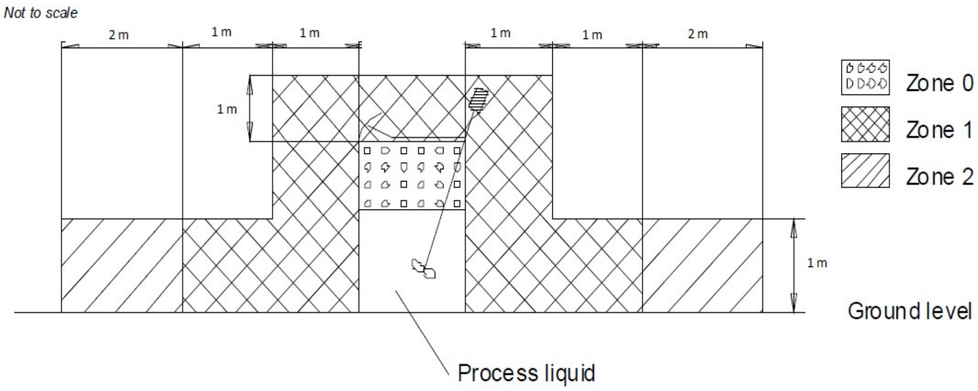


Figure 6.8 The envelop of external zones (Example of the fixed mixing vessel)

6.3 Step 2: ATEX-HOF Ignition Source Assessment

Ignition source assessment is the second step to go through if the zone classification is determined as dangerous zone.

Step 2-1: Presence of potential ignition sources

Potential ignition sources are identified based on 13 possible ignition sources listed in EN 1127-1 (Table 6.12).

Table 6.12 Possible ignition sources according to EN 1127-1 (2011)

- Hot surfaces	- Electromagnetic waves
- Flames, hot gases	- Ionizing radiations
- Mechanically generated sparks	- High-frequency radiation
- Sparks from electrical equipment	- Ultrasonic
- Static electricity	- Adiabatic compression
- Stray electric currents and cathodic corrosion protection	- Chemical reactions
- Lightning	

Once the presence of the ignition source is identified, the frequency of occurrence will be assessed (EN 13463-1, 2009):

1) occurrence *during normal operation* is the situation when the equipment are operating for their intended use within their design parameters;

2) occurrence *during foreseeable malfunction* is the situation when the equipment/person do not perform the intended function/tasks; and such disturbances are known to occur in practice;

3) occurrence *during rare malfunction* is the situation that type of malfunction caused by equipment and/or person may happen only in rare instances.

4) *not relevant* is applied when the situation is not mentioned above.

Step 2-2: Effective ignition sources assessment

It is known that one has to supply initial ignition energy to initiate combustion process. A flammable mixture air can be ignited by an external source of energy such as electric spark, a naked flame, hot vessel walls, etc. It is possible to ignite any flammable mixture only when the maximum generated energy is enough to ignite the mixture (above the minimum ignition energy, MIE).

Step 2-3: Final ignition likelihood estimation

In case that identified potential ignition source is effective, applied barriers and relevant human interventions should be considered. The Event tree has been built. There is one technical barrier applied: the ground system. As the provided technical document: $\underline{P_{tbf} = 3.83\times10^{-4}}$.

The operational barriers and other relevant operational activities are conducted by two people:

- one is the operator performing daily tasks in a normal operation condition (Scenario 1); and
- another is the maintainer conducting the maintenance activities (Scenario 2).

According to the general working context and their personal working performances, the HEP were estimated by applying FUZZY CREAM. HEP (operator) =$\underline{5.01\times10^{-3}}$. HEP (maintainer) =$\underline{1.58\times10^{-2}}$.

For each identified emission source (if it is not the zone NE), both internal and external ignition source assessment were conducted. The final ignition likelihood is assessed in the conservative way. The maximum value of the ignition likelihood among all identified potential ignition sources will be chosen as the final result.

Internal Ignition Source Assessment 1): Flames, Hot gases due to the hot work

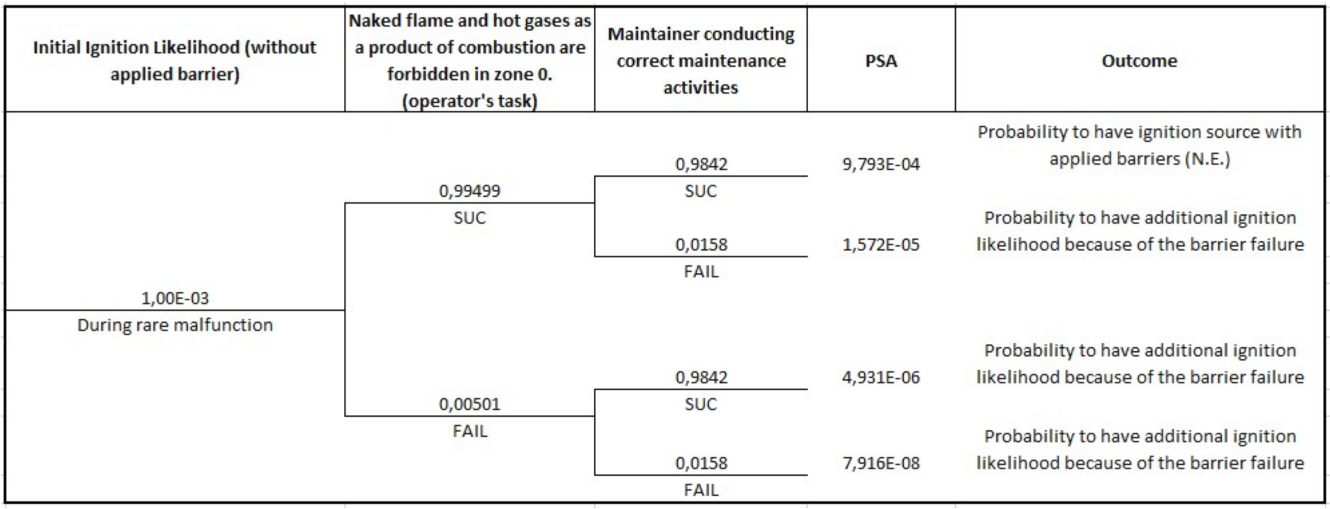


Figure 6.9 Event tree analysis – Flames, hot gases due to the hot work

Table 6.13 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure (B+C+D)	**Final Ignition Likelihood**
Not relevant	2,073E-05 (Rarely)	**Rarely**

Conclusion: In case of the applied barrier failure, the probability to have additional ignition likelihood is higher than the initial ignition likelihood with applied barrier succeeding. Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional ignition likelihood.

<u>Internal Ignition Source Assessment 2):</u> Mechanical Sparks due to the use of improper manual tools

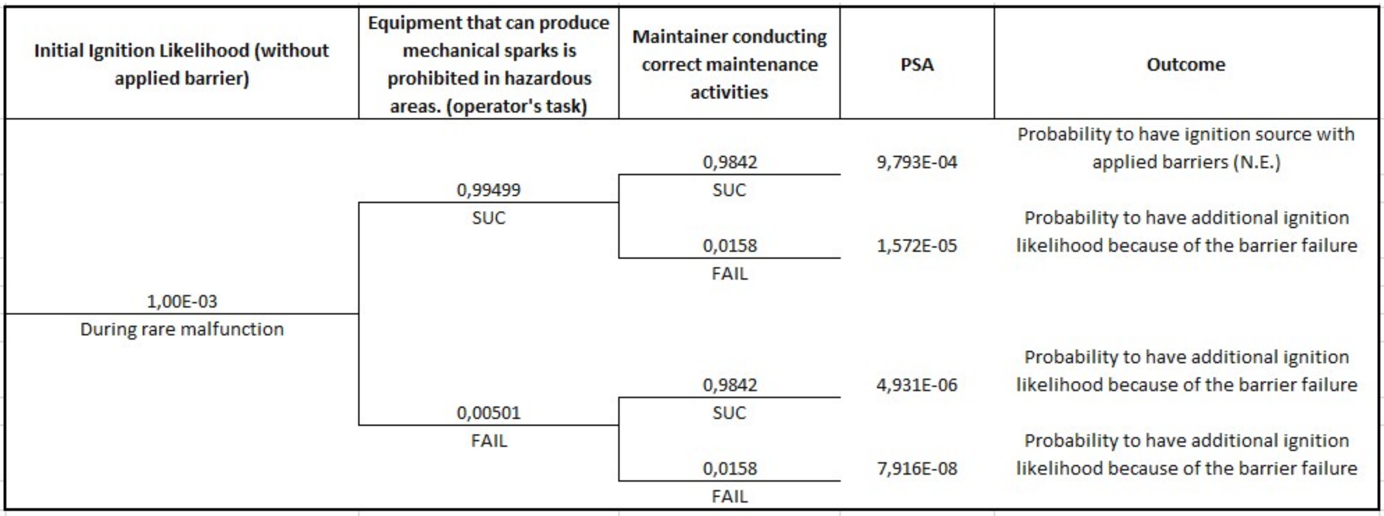


Figure 6.10 Event tree analysis – Mechanical Sparks due to the use of improper manual tools

Table 6.14 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure	**Final Ignition Likelihood**
Not relevant	2,073E-05 (Rarely)	**Rarely**

Conclusion: In case of the applied barrier failure, the probability to have additional ignition likelihood is higher than the initial ignition likelihood with applied barrier succeeding. <u>Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional ignition likelihood.</u>

Internal Ignition Source Assessment 3): Static electricity due to the use of metallic materials

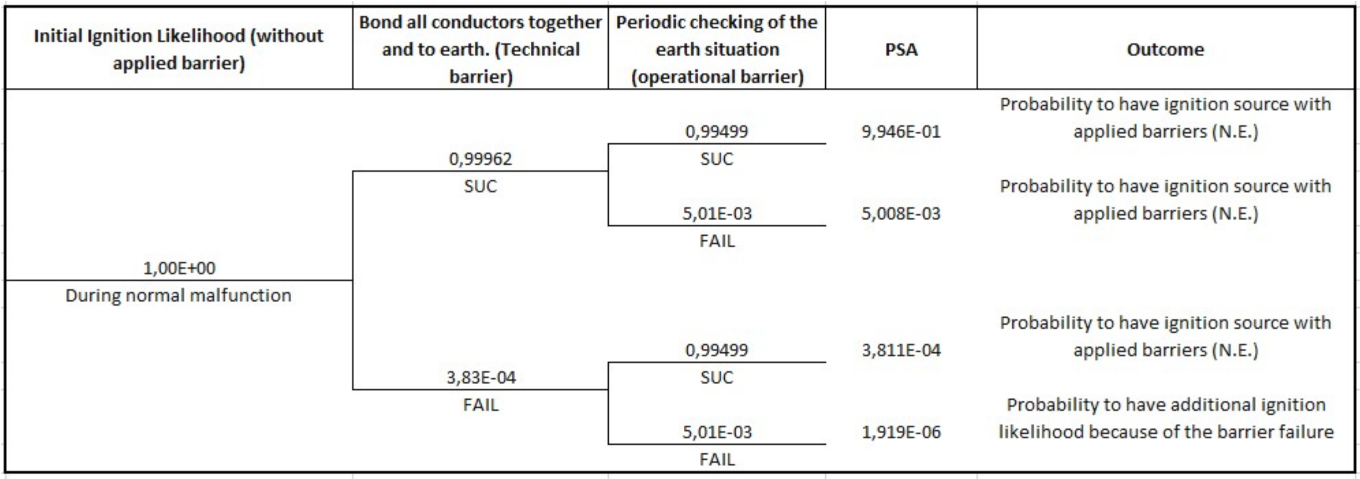


Figure 6.11 Event tree analysis – Static electricity due to the use of metallic materials

Table 6.15 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure	**Final Ignition Likelihood**
Not relevant	1,919E-06 (Not relevant)	**Not relevant**

Conclusion: Even in case of the applied barrier failure, the probability to have additional ignition likelihood is still in the range of initial ignition likelihood with applied barrier succeeding. Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial result assessed.

Table 6.16 ATEX-HOF Ignition source assessment **(Internal assessment result: Rarely)**

1-Presence of potential ignition sources					**2-Effectiveness**	**3-Final ignition likelihood**			
Potential ignition sources		**Motivation for assessment**	**Frequency of occurrence (without applied barriers)**	**Initial Ignition Likelihood P_{IG} (without applied barriers)**		**Barriers applied**	**Probability to have additional ignition likelihood**	**Frequency of Occurrence (including applied barriers)**	**Final Ignition Likelihood**
Internal Ignition Sources	Hot Surface	The temperature inside and outside of the equipment is less than the auto ignition temperature of flammable substances.	Not Relevant	--	N	--	--	--	N.E.
		It can be present due to the friction of moving parts (e.g. the agitator) in case of failure. However, during normal operation and in case of failure, work equipment cannot give rise to incendive friction, impact or abrasion sparks in hazardous areas.	Not Relevant	--	N	--	--	--	N.E.
	Flames, Hot gases	Flames and hot gases may be present due to the hot work during maintenance activities.	During rare malfunction	1×10^{-3}	Y	Naked flame and hot gases as a product of combustion are forbidden in zone 0. Meanwhile, the maintenance is performed by following the hot work permit requirements and procedures. (maintainer & operator)	2.073×10^{-5}	During rare malfunction	Rarely
	Mechanical Sparks	It can be present due to the impact of moving parts (e.g. the agitator) in case of failure. However, during normal operation and in case of failure, work equipment cannot give rise to incendive friction, impact or abrasion sparks in hazardous areas.	Not Relevant	--	N	--	--	--	N.E.
		Mechanical sparks may be generated from the use of improper manual tools during the maintenance activities.	During rare malfunction	1×10^{-3}	Y	Equipment that can produce mechanical sparks is prohibited in hazardous areas. Meanwhile, the maintenance is performed under the safety requirements and the procedures (maintainer & operator)	2.073×10^{-5}	During rare malfunction	Rarely
	Static Electricity	Parts of non-metallic material are present. With received technical documentation, the materials are made of antistatic material.	Not relevant	--	N	--	--	--	N.E.
		The use of metallic materials may potentially cause disruptive discharges.	During normal operation	1	Y	1) Bond all conductors together and to earth. (technical barrier) 2) Periodic checking of the earth situation with taking into account of specific procedures. (operator)	1.919×10^{-6}	Not relevant	N.E.

<u>External Ignition Source Assessment 1):</u> Flames, Hot gases due to the hot work

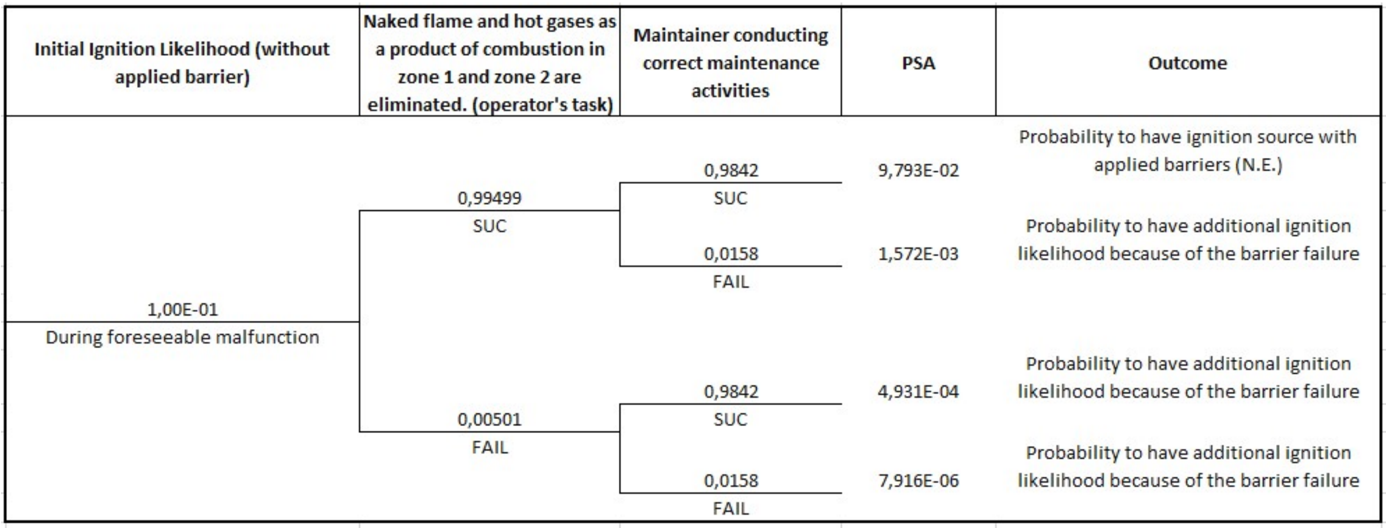


Figure 6.12 Event tree analysis – Flames, hot gases due to the hot work

Table 6.17 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure (B+C+D)	**Final Ignition Likelihood**
Not relevant	2,073E-03 (Occasionally)	**Occasionally**

Conclusion: In case of the applied barrier failure, the probability to have additional ignition likelihood is higher than the initial ignition likelihood with applied barrier succeeding. <u>Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional ignition likelihood.</u>

External Ignition Source Assessment 2): Mechanical Sparks due to the use of improper manual tools

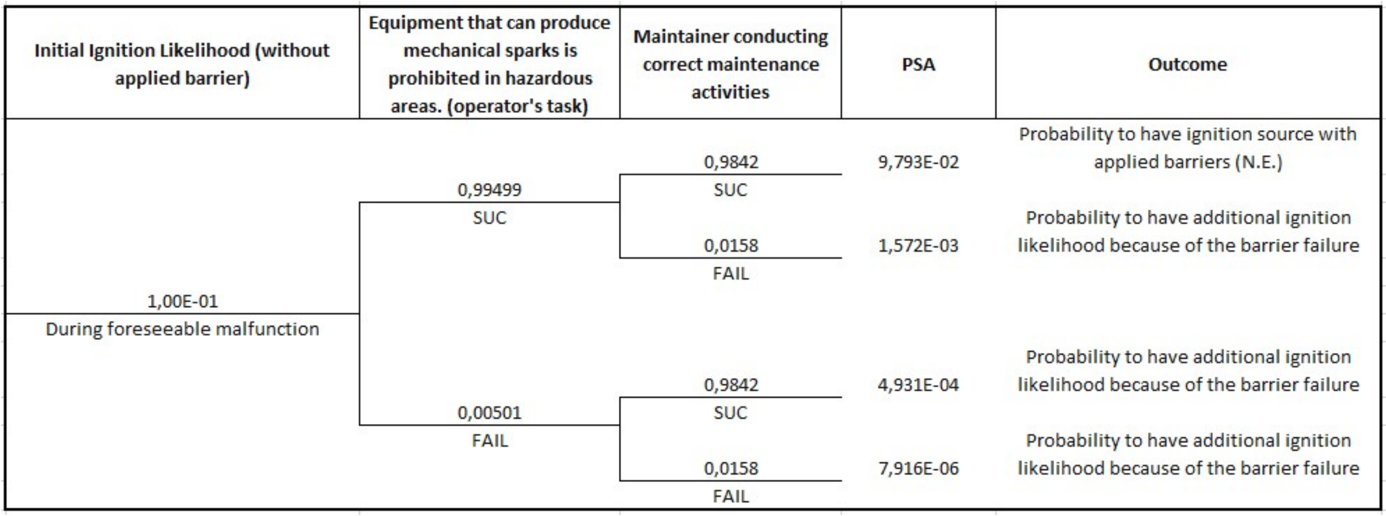


Figure 6.13 Event tree analysis – Mechanical Sparks due to the use of improper manual tools

Table 6.18 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure (B+C+D)	**Final Ignition Likelihood**
Not relevant	2,073E-03 (Occasionally)	**Occasionally**

Conclusion: In case of the applied barrier failure, the probability to have additional ignition likelihood is higher than the initial ignition likelihood with applied barrier succeeding. Thus, this is not a sufficient safety culture condition where the result from HOF influence leading to have additional ignition likelihood.

<u>External Ignition Source Assessment 3):</u> Static Electricity due to the use of metallic materials

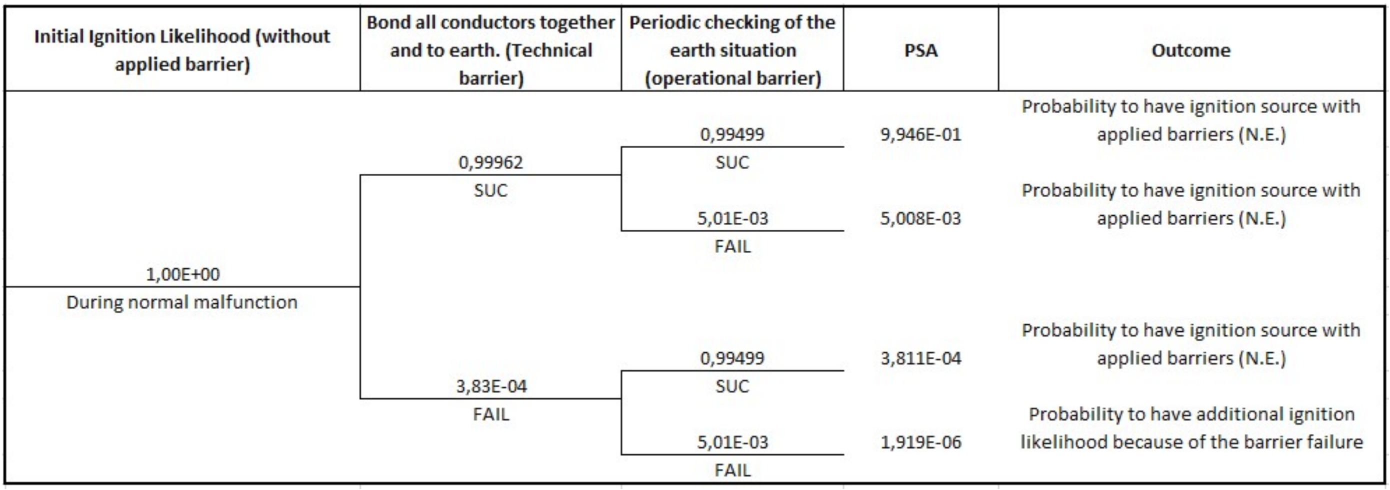


Figure 6.14 Event tree analysis – Static Electricity due to the us of metallic materials

Table 6.19 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure (B+C+D)	**Final Ignition Likelihood**
Not relevant	1,919E-06 (Not relevant)	**Not relevant**

Conclusion: Even in case of the applied barrier failure, the probability to have additional ignition likelihood is still in the range of initial ignition likelihood with applied barrier succeeding. Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial result assessed.

<u>External Ignition Source Assessment 4):</u> Stray electrical currents, cathodic and corrosion protection

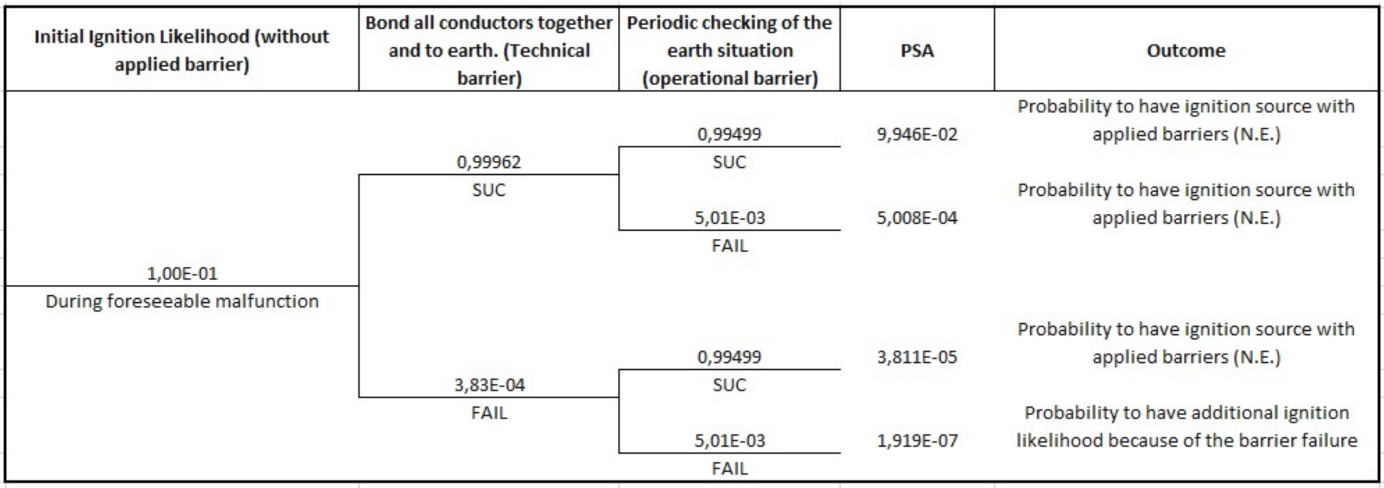


Figure 6.15 Event tree analysis – Stray electrical currents, cathodic and corrosion protection

Table 6.20 Final Ignition Likelihood Determination

Initial Ignition Likelihood with applied barrier succeeding	Probability to have additional ignition likelihood because of the barrier failure (B+C+D)	**Final Ignition Likelihood**
Not relevant	1,919E-07 (Not relevant)	**Not relevant**

Conclusion: Even in case of the applied barrier failure, the probability to have additional ignition likelihood is still in the range of initial ignition likelihood with applied barrier succeeding. Thus, this is a good safety culture condition where the result from HOF influence doesn't change the initial result assessed.

Table 6.21 ATEX-HOF Ignition source assessment **(External assessment result: Occasionally)**

1-Presence of potential ignition sources					**2-Effectiveness**	**3-Final ignition likelihood**			
Potential ignition sources		**Motivation for assessment**	**Frequency of occurrence (without applied barriers)**	**Initial Ignition Likelihood P_{IG} (without applied barriers)**		**Barriers applied**	**Probability to have additional ignition likelihood**	**Frequency of Occurrence (including applied barriers)**	**Final Ignition Likelihood**
External Ignition sources	Hot Surface	Electrical equipment may generate hot surface in case of failure. However, the temperature inside and outside of the equipment is less than the auto ignition temperature of flammable substances.	Not Relevant	--	N	--	--	--	N.E.
	Flames, Hot gases	Flames and hot gases may be present due to the hot work during maintenance activities.	During foreseeable malfunction	1×10^{-1}	Y	Naked flame and hot gases as a product of combustion in zone 1 and zone 2 are eliminated. Meanwhile, the maintenance is performed by following the hot work permit requirements and procedures. (maintainer & operator)	2.073×10^{-3}	During foreseeable malfunction	Occasionally
	Mechanical Sparks	Mechanical sparks may be generated externally from the use of improper manual tools during the normal operation and maintenance activities.	During normal operation	1	Y	Inside the painting mixing room there are only ATEX required manual tools (technical barrier)	--	Not relevant	Occasionally
			During foreseeable malfunction	1×10^{-1}	Y	Equipment that can produce mechanical sparks, during the normal operation, is prohibited in hazardous areas. (operator) Maintainer from outside the paint mixing room is performing the maintenance with the safety requirement and following the procedure, e.g. always choose the ATEX required manual tools. (maintainer)	2.073×10^{-3}	During foreseeable malfunction	
	Electrical Sparks	ATEX required electrical equipment are applied so that it is impossible to be effective even in case of failure.	Not relevant	--	N	--	--	--	N.E.

Table 6.21 ATEX-HOF Ignition source assessment **(External** - cont.**)**

1-Presence of potential ignition sources					**2-Effectiveness**	**3-Final ignition likelihood**			
Potential ignition sources		**Motivation for assessment**	**Frequency of occurrence (without applied barriers)**	**P_{IG}**		**Barriers applied**	**Probability to have additional ignition likelihood**	**Frequency of Occurrence (including applied barriers)**	**Final Ignition Likelihood**
External Ignition sources	Static Electricity	The use of metallic materials may potentially cause disruptive discharges.	During the normal operation	1	Y	1) Bond all conductors together and to earth. (technical barrier) 2) Periodic checking of the earth situation with taking into account of specific procedures. (operator)	1.919×10^{-6}	Not relevant	N.E.
		Parts of non-metallic material are present. With received technical documentation, the materials are made of antistatic material.	Not relevant	--	N	--	--	--	N.E.
		Persons who are insulated from earth can easily acquire and retain an electrostatic charge. However, since the work equipment, during normal operation and in case of failure, cannot give rise to incendive discharges in hazardous areas, static electricity is not possible generated by person.	Not relevant	--	N	--	--	--	N.E.
	Stray electrical currents, Cathodic and Corrosion protection	It is possible to be present during the maintenance (e.g. welding operations) because stray currents can flow in electrically conductive systems or parts of systems.	During foreseeable malfunction	1×10^{-1}	Y	1) The potential compensation system is provided, such as the grounding system. Bond all conductors together and to earth. (technical barrier) 2) Periodic checking the compensation system with taking into account of specific procedures. (operator)	1.919×10^{-7}	Not relevant	N.E.

6.4 Step 3: ATEX-HOF Damage Analysis

ATEX-HOF damage analysis relies on the Area classification result and other factors. Given to the guidance of the ATEX risk assessment application (Cavaliere and Scardamaglia, 2005; and Cavaliere, 2011), the formulas and indexes support the calculation of the semi-quantitative parameter D_{HOF}. If the zone prediction changes in the ATEX-HOF Area classification, the ID value is also changed as ID_{HOF}.

$$D_{HOF} = ID_{HOF} + PL + KG + VZ + CN \text{ (for gas)} \qquad \text{Eq. (6.1)}$$

6.5 Step 4: ATEX-HOF Risk Evaluation

According to Table 4.9 in Chapter 4, the values of P_{HOF}, C_{HOF}, and D_{HOF} can be determined through the results from Step 1 to Step 3. The ATEX-HOF risk (R_{HOF}) was the multiplication of P_{HOF}, C_{HOF}, and D_{HOF} ($R_{HOF} = P_{HOF} \times C_{HOF} \times D_{HOF}$), and the final risk level can be ranked.

Table 6.22 Traditional ATEX Risk evaluation result for the basic paint mixing unit
(in case of relevant operational activities and applied barriers success)

Emission Source	Area Classification	P	Effectiveness of Ignition Source	C	D	R = P×C×D	Risk Level
Paint Loading Container	Internal (liquid surface)	3	Internal: Not relevant	0	3	R<1	Negligible
	External (opening)	2	External: Not relevant	0	2	R<1	Negligible
	External (leakage)	1		0	1	R<1	Negligible
Fixed process mixing vessel	Internal (liquid surface)	3	Internal: Not relevant	0	3	R<1	Negligible
	External (opening)	2	External: Not relevant	0	2	R<1	Negligible
	External (leakage)	1			1	R<1	Negligible
Supply system	Internal (liquid surface)	3	Internal: Not relevant	0	3	R<1	Negligible
	External (structural emission)	2	External: Not relevant	0	2	R<1	Negligible
	External (leakage)	1			1	R<1	Negligible

Table 6.23 The ATEX-HOF Risk evaluation result for the basic paint mixing unit
(in case of relevant operational activities and applied barriers failure)

Emission Source	**Area Classification**	P_{HOF}	**Effectiveness of Ignition Source**	C_{HOF}	D_{HOF}	$R_{HOF} = P_{HOF} \times C_{HOF} \times D_{HOF}$	**Risk Level**
Paint Loading Container	Internal (liquid surface)	3	Internal: Rarely	1	3	9	Low
	External (opening)	2	External: Occasionally	2	2	8	Low
	External (leakage)	2			2	8	Low
Fixed process mixing vessel	Internal (liquid surface)	3	Internal: Rarely	1	3	9	Low
	External (opening)	2	External: Occasionally	2	2	8	Low
	External (leakage)	2			2	8	Low
Supply system	Internal (liquid surface)	3	Internal: Rarely	1	3	9	Low
	External (structural emission)	2	External: Occasionally	2	2	8	Low
	External (leakage)	2			2	8	Low

6.6 Results for the ATEX-HOF Risk Assessment

As mentioned above, the risk level of the basic paint mixing unit is NEGLIGIBLE for all the identified emission sources (internal and external sides) in case of the following applied barriers and/or relevant operational activities correctly performing:

1) Naked flame and hot gases as a product of combustion are forbidden in zone 0, and in zone 1 and zone 2 are eliminated.
2) The maintenance is performed under the safety requirements (e.g. hot work permit).
3) The maintenance is performed following the required procedures.
4) Equipment that can produce mechanical sparks is prohibited in hazardous areas.
5) Periodic checking of the earth situation with taking into account of specific procedures.
6) Inside the paint mixing room there are only ATEX required manual tools.
7) Periodic checking the compensation system with taking into account of particular procedures.
8) People inside the room are always wearing the antistatic clothes and shoes.
9) Even in case of changing operators, maintainers, or equipment, the ATEX risk needs to be re-evaluated.

However, when taking into account of the failure of applied barriers and/or relevant operational activities, the risk level of the basic paint mixing unit goes up to LOW level. Risk mitigation measures should be implemented in a long time interval.

Chapter 7. Discussion

Chapter Objectives:

7.1 Sensitivity about the HOF Influence

7.2 Applicability

7.3 Cost Analysis

7.4 Feedback from Stakeholders

Chapter 7. Discussion

7.1 Sensitivity about the HOF Influence

In nowadays, the change in safety has focused on developing good safety cultures that positively influence human behavior at work to reduce errors and violations. Safety culture is not a difficult idea, but it is generally considered as “trust”, “values” and “attitudes”, which is difficult to clarify the meaning in practise. The ATEX-HOF Methodology deals with the HOF influence on the identified ATEX hazards. The Event tree based probabilistic assessment method has been introduced in order to quantify the HOF influence. It can be concerned as an attempt to handle safety cultures (with HOF influence) in practice via the integration of the risk assessment.

1) With a sufficient (or Good) safety culture, results coming from the ATEX-HOF Methodology would be as the same as the traditional methodology.

Risk Level (The ATEX-HOF Methodology) = Risk Level (Traditional methodology)

2) However, with an insufficient (or Poor) safety culture, results coming from the ATEX-HOF Methodology would be different, which should be the integration of the result taking from the traditional methodology and the HOF influence.

Risk Level (The ATEX-HOF Methodology) = Risk Level (Traditional methodology) + HOF Influence

7.2 Applicability

ATEX (explosive atmosphere) risk assessment here is required when any equipment or protective systems are intended for use in potentially explosive atmospheres. Those industries can be classified as:

1) ATEX Equipment End-users, such as: process industries (e.g. food industry, chemical industry, etc.), manufacturing industries (e.g. automotive manufacturing industry), energy industries (e.g. power plant), and transportation sector.

2) ATEX Equipment Producers: Directive 94/9/EC defines the minimum technical requirements and conformity assessment procedures, to be applied before the equipment intended for use in potentially explosive atmospheres workplace. Although the ATEX risk assessment is generally applied for a workplace risk assessment, here it is also applied where the industries produce ATEX equipment and prepare for the ATEX Equipment End-user market.

7.3 Cost Analysis

The additional consuming time, people involved, process interruption, and the source request are considered (Table 7.1). For each analysis, additional 2-4 minutes are required. The additional source supports are the FUZZY CREAM tool and the Event tree instrument. Additional works include: a) identification of applied technical barriers and human interventions; b) estimation of failure probability of applied technical barriers and relevant human interventions; c) Event Tree Analysis.

7.4 Feedback from Stakeholders

A feedback was collected from the industry where the ATEX-HOF methodology was applied. The questionnaire survey was conducted (Table 7.2). The responses are summarized: a) The ATEX-HOF Methodology covered the process phases: design phase, normal operation, maintenance, and non-routine situation. b) It is necessary to consider HOF within the ATEX risk assessment, and the ATEX-HOF Methodology is helpful for the HOF influence analysis. c) The results coming from the ATEX-HOF Methodology is clear to support decision making. d) The application doesn’t disturb the operations. However, a) half responses concern a high-level of education needed, in order to apply the methodology. b) Half responses concern that conducting the quantitative analysis is a little time consuming.

Table 7.1 Additional costs from the ATEX-HOF Methodology
(Comparing with the traditional ATEX risk assessment methodology)

ATEX Risk Assessment Procedures		**Additional Works to Apply the ATEX-HOF Methodology**	**Additional Time Consumption**	**Additional People Involved**	**Additional Process Interruption**	**Additional Source Support**
1- Area Classification	1.1- Emission Source Identification	--	--	--	--	--
	1.2- Type of Internal Zone	--	--	--	--	--
	1.3- Type of External Zone	**For each source of release analysis**, additional works: - Identification of applied barriers and other operational activities; - Estimation of Probability (Success or Failure) of applied barriers and other human interventions. - Event Tree Analysis - External Zone Determination	With a good training background, the analyst needs **2-4 minutes**.	--	--	- FUZZY CREAM Tool; - Event Tree Analysis support
2- Ignition Source Identification	2.1-Potential Ignition Source Presence	--	--	--	--	--
	2.2-Effective Ignition Source Assessment	--	--	--	--	--
	2.3-Final Ignition Likelihood Estimation	**For each ignition source analysis**, additional works: - Identification of applied barriers and other operational activities; - Estimation of Probability (Success or Failure) of applied barriers and other human interventions. - Event Tree Analysis - External Zone Determination	With a good training background, the analyst needs **2-4 minutes**.	--	--	- FUZZY CREAM Tool; - Event Tree Analysis support
3- Consequence Analysis	Semi-quantitative analysis based on indexes	--	--	--	--	--
4- ATEX Risk Evaluation	Semi-quantitative approach	--	--	--	--	--

Table 7.2 Feedback: the ATEX-HOF Methodology Application in the Paint Mixing Room

1. Is the ATEX-HOF methodology able to be applied in the FAS on-site application? (ATEX: Explosive Atmosphere; HOF: Human and Organizational Factor)			
		Response Percent	**Response Total**
1	Yes	100.00%	4
2	No	0.00%	0
3	No idea	0.00%	0
		skipped	**0**
2. Does the ATEX-HOF methodology cover all process phases? The ATEX-HOF methodology considered (multiple choice):			
		Response Percent	**Response Total**
1	activities in the plant design phase (e.g. original installation of the plant)	50.00%	2
2	activities during the normal operation (e.g. the daily paint mixing activities)	100.00%	4
3	activities during the maintenance activities (e.g. repairing the equipment)	100.00%	4
4	activities in the non-routine situations (e.g. foreseeable malfunction)	100.00%	4
		skipped	**0**
3. Do you think it is necessary to take into account Human and Organizational Factors (HOF) inside the ATEX risk assessment?			
		Response Percent	**Response Total**
1	Yes	100.00%	4
2	No (please specify):	0.00%	0
		skipped	**0**
4. Is the ATEX-HOF methodology helpful that enable you to do the Human risk assessment?			
		Response Percent	**Response Total**
1	Yes	66.67%	3
2	No, (please specify):	33.33%	0
		skipped	**1**
5. Do you think that the ATEX-HOF methodology needs a high-level education background?			
		Response Percent	**Response Total**
1	Yes	50.00%	2
2	No	25.00%	1
3	No idea	25.00%	1
		skipped	**0**
6. Is the developed procedure of the ATEX-HOF methodology complicate to apply?			
		Response Percent	**Response Total**
1	Yes, it is complicate.	25.00%	1
2	No, it is fine.	50.00%	2
3	I have no idea.	0.00%	0
4	Other (please specify):	25.00%	1
		skipped	**0**
Other (please specify): (1)			
1	It depends from the check list, and how much the operation tool will be user friendly.		

Table 7.2 Feedback of the ATEX-HOF Methodology Application in the Paint Mixing Room (cont.)

7. Is the ATEX-HOF methodology a time consuming method?			
		Response Percent	**Response Total**
1	No, it is efficient.	25.00%	1
2	Well, It is a little time consuming, but acceptable.	50.00%	2
3	Yes, it is a waste of time.	25.00%	1
4	I have no idea.	0.00%	0
		skipped	**0**
8. Does the ATEX-HOF risk assessment disturb the operations during the application?			
		Response Percent	**Response Total**
1	No, it is fine.	100.00%	4
2	Sometimes, but it is acceptable	0.00%	0
3	Yes, it frequently disturbs our daily operations	0.00%	0
4	Other (please specify):	0.00%	0
		skipped	**0**
9. Does the results (from the ATEX-HOF risk assessment) match the national or company regulations/standards?			
		Response Percent	**Response Total**
1	Yes	75.00%	3
2	No	0.00%	0
3	I have no idea	25.00%	1
		skipped	**0**
10. Do you think it is necessary to conduct the quantitative analysis instead of the qualitative analysis for the ATEX risk assessment?			
		Response Percent	**Response Total**
1	Yes, we need specific numbers (e.g. probability), in order to know more accurate results.	50.00%	2
2	Well, sometimes, in the critical tasks, we need; however, most of the time, qualitative analysis is enough.	50.00%	2
3	No, qualitative analysis is better. Quantitative analysis (numbers) is useless for us.	0.00%	0
4	I have no idea.	0.00%	0
5	Other (please specify):	0.00%	0
		skipped	**0**
11. Is the result from the ATEX-HOF methodology clear to support decision making?			
		Response Percent	**Response Total**
1	Yes	100.00%	4
2	No	0.00%	0
3	Other (please specify):	0.00%	0
		skipped	**0**
12. Others that you think that needs to improve?			
		Response Percent	**Response Total**
		100.00%	2
1	Question 7: It is not a "waste" of time, just it seems that quite a long time is necessary.		
2	It was not showed how to measure CPC 9 - Crew collaboration Quality, and how it depends from single person? What is the effect of Human nature of the single worker? And how do you address Human nature of single worker?		
		skipped	**2**

Chapter 8. Conclusion

Chapter Objectives:

8.1 Summary of the Research

8.2 Strengths of the Research Work

8.3 Further Work

Chapter 8. Conclusion

8.1 Summary of the Research

ATEX (explosive atmosphere) risk assessment is required when any equipment or system potentially causes explosive atmospheres. Despite many operations on plant and equipment containing dangerous substances are performed by operators, influences of human and organizational factor (HOF) are mostly neglected from the ATEX risk assessment. This research work, according to the overview of the general risk assessment and human factor integration techniques, focuses on the HOF influence on a specific application domain: the ATEX (explosive atmosphere) risk assessment domain. It aims to propose an advanced methodology, in order to analyze the HOF influence on ATEX hazards. The roadmap of this research was followed:

Stage 1. Introduction & Background

Current risk assessment relevant safety standards were reviewed, and the current application in industries was investigated via the interview. However, with reviewing the risk assessment methodologies suggested by those standards, Human and Organizational Factor (HOF) is not sufficient handled factor in a risk assessment, but can be identified among all phases of a system life cycle. Meanwhile, the 16 industries' interviews were conducted by all INNHF fellows. As a part of the results, it has also shown that across all sectors use standards to support their risk assessment and safety management. The international standards most used were OHSAS 18001, ISO 9001, ISO 14001, and ISO 31000. No human factors standards were mentioned by any interviewee.

Hence, questions occur: "Are current safety standards and their suggested risk assessment methodologies enough to apply without considering human and organizational factors (HOF)?" "How to analyse the HOF influence on identified hazards"? With these questions, in Chapter 2, an overview of current Risk Assessment Methodologies and Human Factor Integration (HFI) techniques was conducted, in order to try to find a way on the HFI.

Stage 2. Literature Review

ISO/IEC 31010:2009 described 31 risk assessment methodologies. Most of them are qualitative methods. In addition, Marhavilas, et al. (2011) reviewed the scientific literature from 2000-2009, and summarized 18 risk assessment methodologies. The review work was mainly based on their contributions. The review of the common applied risk assessment methodologies was conducted in three groups: qualitative, quantitative, and hybrid groups.

Evans (1976) explained that human reliability is a probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system. Human reliability analysis (HRA) is a method that human reliability is estimated. The review work on HRA techniques was based on Hollnagel (1998) consideration with two categories: 1) Task-dominant approaches that concerns human doing a task as the consequence of success and failure; and 2) Cognition-dominant approaches concerns human cognitions as causes of the human failure.

According to the reviewed work, in the risk identification phase, HOF can be identified as different type of sources to support the risk identification. In the risk analysis phase, HRA technique provides the instruments that enable to support both the qualitative and the quantitative analysis. In the risk evaluation phase, HOF was proposed to be integrated as a part of the traditional risk assessment which can be interactive with the functional analysis result.

Stage 3. The ATEX-HOF Methodology Development

Cavaliere and Scardamaglia (2005) and Cavaliere (2011) provided a methodology for the ATEX risk assessment that fulfills the requirements of both ATEX Directive 94/9/EC, Directive 99/92/EC, and related standards. Here, the ATEX-HOF methodology was proposed based on this methodology. In order to address two challenges: 1) HOF influence on identified ATEX hazards; and 2) HOF quantification, the framework of the ATEX-HOF methodology was developed with four steps: 1) Area classification, 2) Ignition source identification, 3) Damage analysis, and 4) ATEX Risk evaluation.

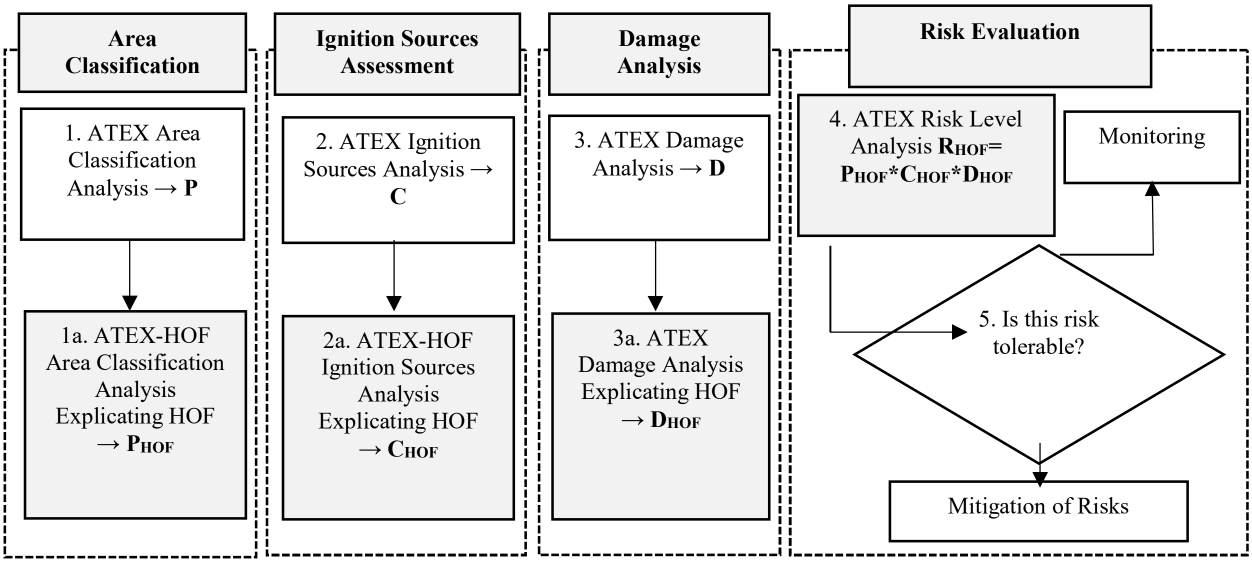


Figure 8.1 The framework of the ATEX-HOF methodology (Geng, et al., 2015a)

On the other hand, two representative HRA techniques (THERP and FUZZY CREAM) were applied and compared. The application of FUZZY CREAM provided a simpler, rapid, but effective way to support the Human Reliability Analysis (HRA).

Stage 4. Application of the ATEX-HOF Methodology

Two applications of the ATEX-HOF Methodology in real industries (a food industry and an automotive industry) were conducted. Meanwhile, the traditional and ATEX-HOF Methodology were compared, in order to see the performance of the ATEX-HOF Methodology, and then to improve the developed methodology. In the end, the research work is completed.

8.2 Strengths of the Research Work

The ATEX-HOF methodology provides a quantitative risk analysis approach with taking into account of the Human and Organizational Factors (HOF). Inside each phase, clearly assessment goals are identified which are enable to conduce the ATEX risk assessment with simplified 'step-by-step'. An event tree based probabilistic assessment has been introduced. Hence, the ATEX-HOF risk assessment becomes more complete than the traditional approach.

The on-site applications shown how taking into account HOFs is particular important in companies where the usual hypothesis of the correctness of operator intervention (in maintenance, normal operations, and emergency) could bring to not conservative results. The applied operational (HOF) barriers explicated in the analysis can be used to support for defining a more detailed set of operational procedures, which is able to maintain the risk level evaluated.

8.3 Further work

In future, 1) more case studies are expected to apply, in order to validate the performance of the ATEX-HOF Methodology. 2) Relevant software is expected to develop, with the aim of supporting safety analyst easier to apply the ATEX-HOF Methodology (e.g. reducing the time for the calculation). 3) Standardization: the ATEX-HOF Methodology is expecting to propose as ANNEX (for alternative method) to support and complete the relevant safety standards.

Annex A. Proposals for the ATEX Relevant Standards

Chapter Objectives:

A.1 Relevant Standards

A.2 Proposal 1: Integration of the ATEX-HOF Methodology into IEC 60079-10-1

A.3 Proposal 2: Integration of the ATEX-HOF Methodology into EN 13463-1

Annex A. Proposals for the ATEX Relevant Standards

A.1 Relevant Standards

The ATEX Area classification deals with situations of normal operation, maintenance, and predictable failures; and it is mainly referred to two standards: IEC 60079-10-1 (for gas, 2008) and IEC 60079-10-2 (for dust, 2009). For specific applications, different countries developed dedicated guidelines, as in Italy CEI 31-35 (2012) and CEI 31-56 (2007).

Ignition source assessment is the second step to go through if the zone classification is determined as a dangerous zone. EN 13463-1 (2009) is a standard for Non-electrical Equipment for Use in Potentially Explosive Atmospheres. The standard aims to provide the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres. Following the procedure, the equipment can be verified and marked with ATEX markings for the further use in different ATEX zones' working environment. Since EN 13463-1 covers most common ignition sources and explicates the procedure to identify 13 ignition sources listed in EN 1127-1 (2011), the ATEX-HOF methodology takes a part of EN 13463-1 to apply as the method for the ignition source assessment. As mentioned above, the following standards are mainly applied among conducting the ATEX risk assessment:

Table A.1 Targeted ATEX Relevant Standards

Relevant Standards/ ANNEX/Guidelines	Description of Relevant Standards/ ANNEX/Guidelines
IEC 60079-10-1, 2008, Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres. **IEC 60079-10-2**, 2009, Explosive atmospheres - Part 10-2: Classification of areas - Explosive dust atmospheres. **EN 1127-1,** 2011, Explosive atmospheres - explosion prevention and protection - Part 1: Basic concepts and methodology. **EN 13463**, 2009, Non-electrical equipment for use in potentially explosive atmospheres.	**IEC 60079-10-1:** This part of IEC 60079 is concerned with the classification of areas where flammable gas or vapour or mist hazards may arise and may then be used as a basis to support the proper selection and installation of equipment for use in a hazardous area. **IEC 60079-10-2**: The standard is concerned with the identification and classification of areas where explosive dust atmospheres and combustible dust layers are present, in order to permit the proper assessment of ignition sources in such areas. **EN 1127-1:** This European Standard specifies methods for the identification and assessment of hazardous situations leading to explosion and the design and construction measures appropriate for the required safety. This is achieved by risk assessment and risk reduction. **EN 13463-1:** This European Standard specifies the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres in air of gas, vapour, mist and dusts.
IMPROVEMENTS ON EXISTING METHODS/STANDARDS MENTIONED ABOVE The integrated ATEX-HOF methodology is proposed, with the aim of providing an advanced methodology to analyze HOF influences on ATEX hazards. Among these procedures mentioned in the standards above, HOF is identified as a type of barriers that can influence on determining the external zone (ATEX Area classification) and the final ignition likelihood (ATEX Ignition source identification). The Event tree is introduced to support the quantification analysis.	

A.2 Proposal 1: Integration of the ATEX-HOF Methodology into IEC 60079-10-1

The scope of IEC 60079-10-1 (2008) concerns with the classification of areas where flammable gas or vapour or mist hazards may arise and may then be used as a basis to support the proper selection and installation of equipment for use in a hazardous area. General procedures include:

1) **Source of release identification:** Each item of the process equipment which contains flammable materials is considered as a potential release source, such as a tank, pump, pipeline, vessel, etc.

2) **Determining the internal zone** of the identified release source, on the basis of the grade of release and the ventilation.

3) **Determining the external zone** of the identified release source is on the basis of release rate, lower explosive limit (LEL), ventilation and other factors (such as climatic conditions and topography).

Among these procedures, **HOF is identified as a type of barriers and/or relevant operational activities that can influence on determining the external zone.** In case to take into account of HOF influence on the external zone determination, HOF is proposed to be inserted into the clause 5.4.5 of IEC 60079-10-1 (2008) as one of other parameters to be considered.

5.4 Extent of zone

……

Where the source of release is situated outside an area or in an adjoining area, the penetration of a significant quantity of flammable gas or vapour into the area can be prevented by suitable means such as:

a) physical barriers **and/or operational barriers (e.g. maintenance activities, operation inspections)**;

b) maintaining a sufficient overpressure in the area relative to the adjacent hazardous areas, so preventing the ingress of the explosive gas atmosphere;

c) purging the area with sufficient flow of fresh air, so ensuring that the air escapes from all openings where the flammable gas or vapour may enter.

The extent of the zone is mainly affected by the following chemical and physical parameters, some of which are intrinsic properties of the flammable material; others are specific to the process. For simplicity, the effect of each parameter listed below assumes that the other parameters remain unchanged.

5.4.1 Release rate of gas or vapour

……

5.4.5 Other Parameters to be considered

a) Climatic conditions

……

b) Topography

……

c) Human and organizational factors (HOF)

Since many operations on plant and equipment containing dangerous substances are performed by operators, influences of human and organizational factor (HOF) should be taken into account. The HOF can be considered as a type of barriers (technical barriers and/or operational barriers) and/or relevant operational activities with a potential probability to fail. Hence, those human interventions can influence the external zone determination.

For the detailed information to analyze HOF influences on ATEX hazards, an annex is proposed:

Annex X

(informative)

HOF Influence Analysis and An Alternative Approach for the External Zone Determination

X.1 General

The purpose of this annex is to provide guidance in analysing the Human and Organizational Factor (HOF) influences and to extend Clause 5 for the extent of zone determination. The method developed allows the determination of the external zone by

- estimating the initial probability of having an internal explosive atmosphere (Pr_{IN});
- calculating the failure probabilities of applied barriers and other human interventions (Pr_{BF});
- calculating the final likelihood of having an explosive atmosphere (PSA);
- determining the external zone.

It is a quantitative analysis approach that can be used as an alternative approach for the external zone determination if the probability information can be collected.

X.2 HOF influence identification

The external zone depends on the estimated (or calculated) distance over the area that explosive atmosphere exists before it disperses with appropriate safety factors. Where the release spreads in the surrounding area, the penetration of a significant quantity of flammable substances into the area can be influenced by applied barriers (technical barriers and/or operational barriers), human related operating and maintaining activities, and sufficient ventilations. **The extension of the critical external zone must be determined with the consideration of applied barriers and/or other human interventions.**

X.3 PSA Event tree

The Event tree (Papazoglou, 1998) is here introduced for a probabilistic safety assessment (PSA). The initial event (Figure X.1) has an initial probability (Pr_{IN}) that represents the internal explosive atmosphere occurrence. A series of possible paths are constructed by applied barriers and relevant operational activities. Each path is assigned with a probability of failure (Pr_{BF}) or success (Pr_{BS}). The probability allows to calculate the likelihood of having an explosive atmosphere (PSA).

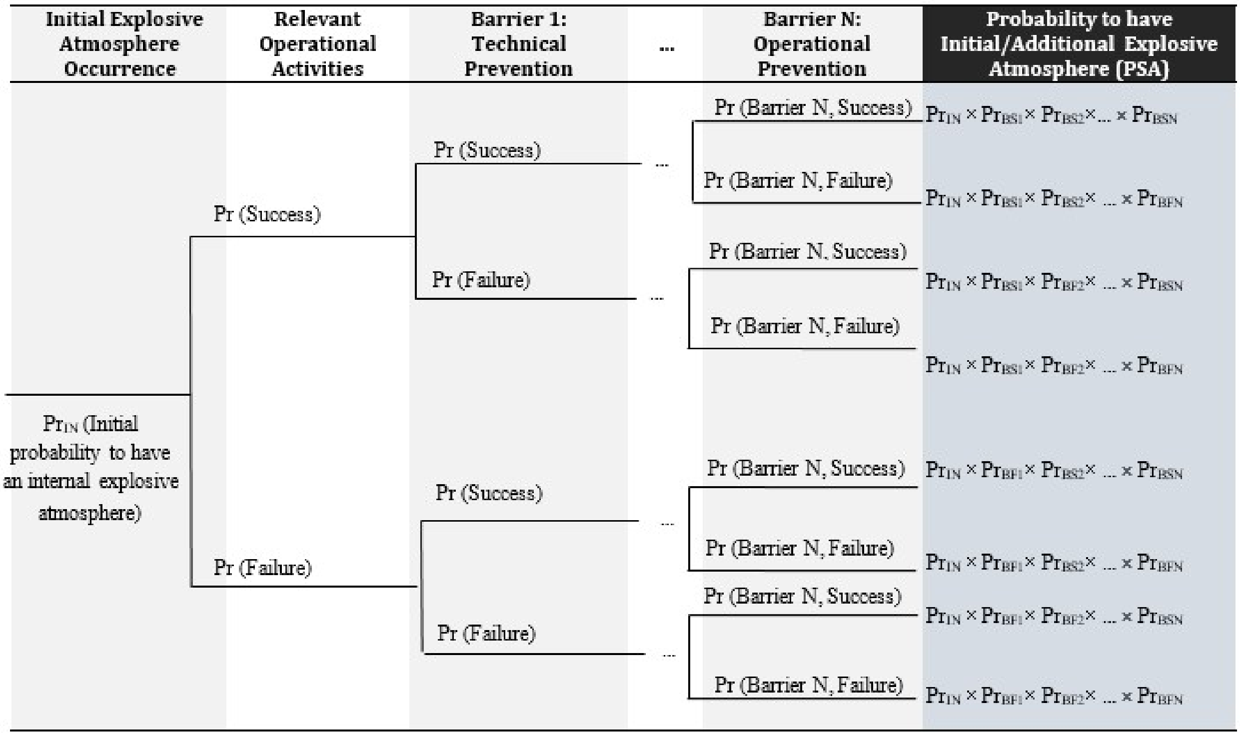


Figure X.1 Event tree structure for the external zone determination

X.3.1 Initial probability of internal explosive atmosphere occurrence (Pr_{IN})

In order to define the Pr_{IN}, Table X.1 is applied which correlates the area classification to the probability of the explosive atmosphere presence.

- In case the equipment/components of a system which includes flammable products is continuously or frequently using, the internal zone is determined as Zone 0/20, and the probability to have explosive atmosphere will be higher than 10^{-1};
- In case the equipment/components of a system which includes flammable products is sporadically using, the internal zone is determined as Zone 1/21, and the probability to have explosive atmosphere will be in the range from 10^{-1} to 10^{-3};
- In case the equipment/components of a system which includes flammable products is not using or infrequently using, the internal zone is determined as Zone 2/22, and the probability to have explosive atmosphere will be in the range from 10^{-3} to 10^{-5}.

Table X.1 Area classification depending on the probability of explosive atmosphere occurrence in a year

Area Classification	Probability of Explosive Atmosphere Occurrence in 365 days (PSA)	Descriptor
Zone 0/20	$P>10^{-1}$	Explosive atmosphere is continuously present, for long periods or frequently.
Zone 1/21	$10^{-1}\geq P>10^{-3}$	Explosive atmosphere is sporadically present, during normal operations.
Zone 2/22	$10^{-3}\geq P>10^{-5}$	Explosive atmosphere is not present during normal operations, or infrequently present, for a short period.

X.4 HEP Estimation: human reliability analysis (HRA) techniques

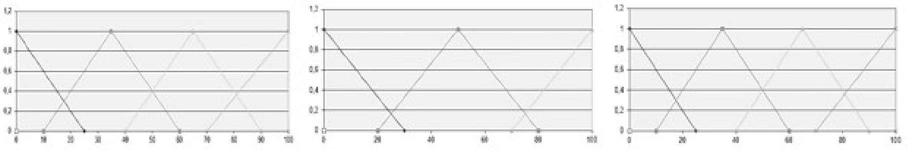
Several types of methodologies are used for identifying and quantifying human error and among them are the Human Reliability Analysis (HRA). Human reliability is the probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system.

X.4.1 FUZZY CREAM

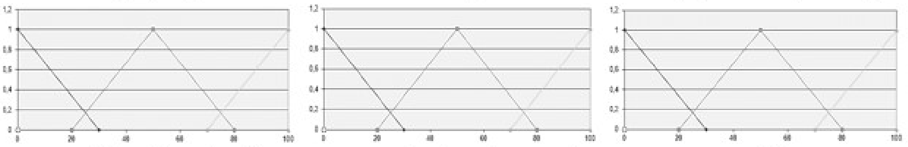
Taking FUZZY CREAM as an example, CREAM with the FUZZY application meets the need for simple, rapid but effective tool, and it can be employed for various industries. CREAM - Cognitive Reliability and Error Analysis Method covers technical, human and organizational factors, and provides a relatively stable HEP output. It provides a two-level method to calculate Human Error Probability (HEP): the basic method and the extended method. In the practice point of view, the basic method enables safety managers making a fast decision with a macro consideration of HEP. The extended method deals with the specific action failure probability. The HEP estimation in our study was based on the CREAM basic method. The basic method uses task analysis to identify human actions, and assesses Common Performance Conditions (CPCs) by judging the expected effects and making a combined score of them with the triplet [$\sum_{\text{reduced}}$, $\sum_{\text{not significant}}$, $\sum_{\text{improved}}$]. The 9 Common Performance Conditions (CPCs) take into account of both human and organizational factors which are:

CPC 1-Adequacy of Organization
CPC 2-Working Conditions
CPC 3- Adequacy of MMI and Operational Support
CPC 4- Availability of Procedures / Plans
CPC 5- Number of Simultaneous Goals
CPC 6- Available Time
CPC 7- Time of Day (Circadian Rhythm)
CPC 8- Adequacy of Training and Experience
CPC9- Crew Collaboration Quality

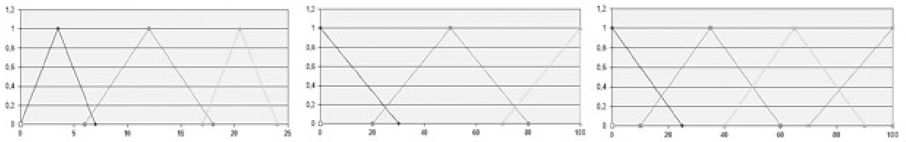
Final results are interpreted through a control mode matrix defined by the Contextual Control Mode (COCOM): 1) Strategic Control, 2) Tactical Control, 3) Opportunistic Control, and 4) Scrambled Control. The COCOM model not only defined the control modes, but also provided HEP probability ranges (Table X.2). Starting from the CREAM basic method, a dedicated tool was developed to apply FUZZY CREAM. Figure X.2 shows the inputs' membership functions. After experts judge the input vector (9 CPCs), the HEP output will be generated by the FUZZY CREAM tool via the Centroid defuzzification method.



CPC 1. Adequacy of Organization CPC 2. Working Conditions CPC 3. Adequacy of MMI and Operational Support



CPC 4. Availability of Procedures/Plans CPC 5. Number of Simultaneous Goals CPC 6. Available Time



CPC 7. Time of the Day CPC 8. Adequacy of Training and Experience CPC 9. Crew Collaboration Quality

Figure X.2 FUZZY Sets of Nice CPC Inputs

Table X.2 Control modes with the logarithm format as Fuzzy output sets

Human Error Probability (HEP)	UOD	Number of Fuzzy Sets	Level/ Descriptors	HEP Ranges	Membership Level Intervals *(Logarithm Format)*
	[0,1]	4	Strategic	$0.5 \times 10^{-5} < P < 1.0 \times 10^{-2}$	-5.3 to -2.3
			Tactical	$1.0 \times 10^{-3} < P < 1.0 \times 10^{-1}$	-3.3 to -1.3
			Opportunistic	$1.0 \times 10^{-2} < P < 0.5$	-2.3 to -0.3
			Scrambled	$1.0 \times 10^{-1} < P < 1.0$	-1.3 to 0

X.5 Results of the ATEX-HOF Area classification

As a result, all identified release sources from both internal and external zone classification of any equipment are summarized in Table X.3. Further, with the sum of extension calculation from all external zones (the vertical and horizontal dimensions), the envelop of the external zones are drawn on the layout to understand the critical area. Therefore, the final analysis is completed.

Table X.3 ATEX-HOF Area classification result

Emission Source	Internal Source of Release	Internal Grade of Release	Internal Zone	External Source of Release	External Grade of Release	Relevant Operational Activities and/or Applied Barriers	PSA (Probability to have additional explosive atmosphere)	External Zone
E.S.	S.R.	Continuous/ Primary/ Secondary	Zone 0/20, Zone 1/21, Zone 2/22, Zone NE	S.R.	Continuous/ Primary/ Secondary	Technical Barriers/ Operational Barriers/ Other relevant operational activities	Integration of : 1) the initial probability (Pr_{IN}); and 2) Prob. of Barrier/operational Failure (e.g. HEP, P_{tbf})	Zone 0/20, Zone 1/21, Zone 2/22, Zone NE

A.3 Proposal 2: Integration of the ATEX-HOF Methodology into EN 13463-1

The scope of EN 13463-1 (2009): This European Standard specifies the basic method and requirements for design, construction, testing and marking of non-electrical equipment intended for use in potentially explosive atmospheres in air of gas, vapour, mist and dusts. Such atmospheres can also exist inside the equipment. The general procedure to conduct the ignition source identification includes:

- Presence of potential ignition sources;
- Effective ignition source assessment;
- Final ignition likelihood estimation.

Among these procedures, **HOF is identified as a type of barriers and/or other human interventions that can influence on the final ignition likelihood estimation.** In case to take into account of HOF influence, HOF is proposed to be inserted into the Annex B.4.3-Determination of Measures in EN 13463-1:2009.

……

B.4.3 Determination of Measures

If the evaluation shows the application is required to meet the target category adequate preventive and/or protective measures are determined in this step (see Table B.3, Column 3). It is necessary to define these measures in such a way that possible ignition sources cannot become effective or the probability of the ignition source becoming effective is sufficiently low. These measures can be both of technical barriers and/or **other human interventions** ……

Table B.3 – Examples for reporting of the determination of preventive or protective measures (step 3) and the concluding estimation and categorisation (step 4)

3			4	5				6	7	8
Measures applied to prevent the ignition source becoming effective			**PSA**	**Frequency of occurrence including applied measures**				**Ignition Likelihood**	Resulting equipment category in respect of this ignition	Necessary restrictions
a	b	c		a	b	c	d			
Description of the measure applied	References (standards, technical rules, experimental results)	Technical documentation		During normal operation	During foreseeable	During rare malfunction	Not relevant			

For the detailed information to analyze HOF influences on ATEX ignition hazards, an annex is proposed:

Annex X

(informative)

HOF Influence Analysis and A Quantitative Approach to Determine the Final Ignition Likelihood

X.1 General

Since many operations on plant and equipment containing dangerous substances are performed by operators, influences of human and organizational factor (HOF) should be taken into account. The purpose of this annex is to provide guidance in analysing the HOF influences and to extend Annex B for the ignition hazard assessment. The method developed allows determining the final ignition likelihood by

- estimating an initial probability of having a potential ignition source (Pr_{IG});
- calculating failure probabilities of applied barriers and other human interventions (Pr_{BF});
- calculating the final likelihood of having an effective ignition source (PSA);
- determining the final likelihood of having an effective ignition source.

It is a quantitative analysis approach that can be used as an alternative approach for the final ignition likelihood determination if the probability information can be collected.

X.2 HOF influence identification

In case that identified potential ignition source is effective, **applied barriers (both of technical barriers and/or operational barriers) and other human interventions can influence the final ignition likelihood.** The Event tree is built (Figure X.1). The initial event is characterized by the initial probability of the ignition source presence (Pr_{IG}). Series paths are constructed by applied barriers and other relevant operational activities. The barrier failures can be result from the technical barrier failure (Pr_{tbf}) and/or the operational failure (HEP). The probability allows calculating the likelihood of having an effective ignition sources. Since the initial assessment of the ignition source presence is a qualitative value, it cannot be calculated directly in the Event tree. Different from Area classification that can take advantage of probability indexes from Italian Guidelines, the ATEX-HOF Ignition source assessment linked with the uniform probability ranges from the Area classification (Table X.1).

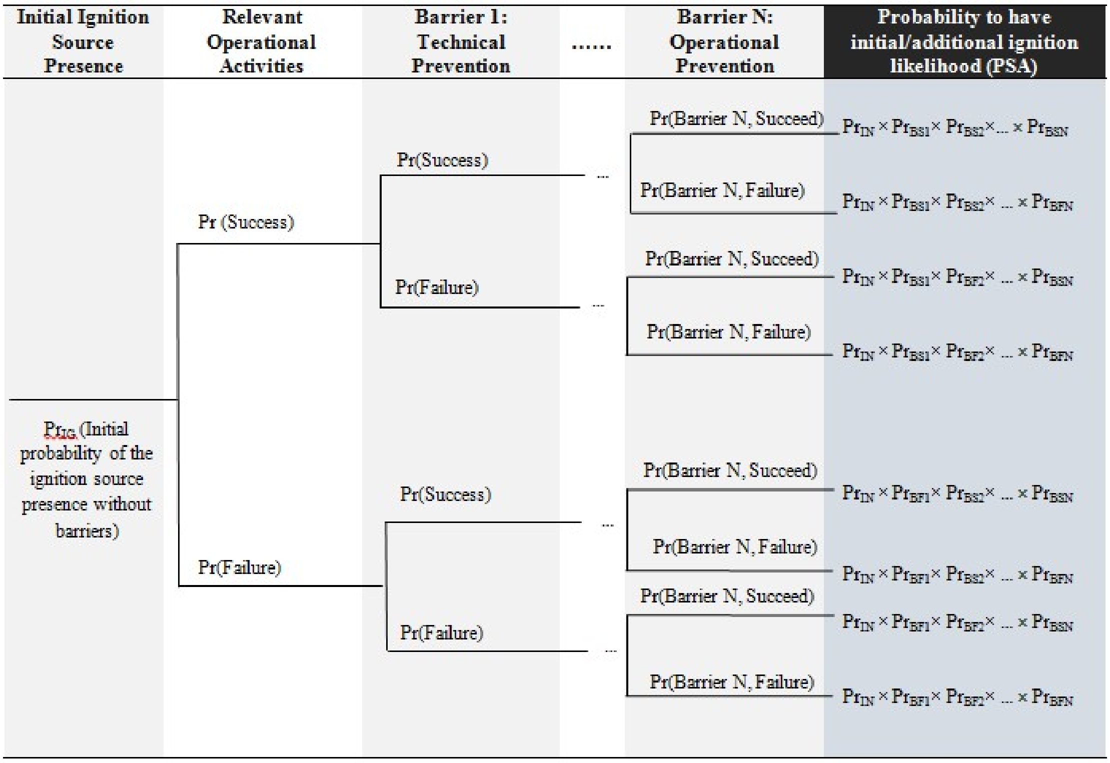


Figure X.1 PSA Event tree for the final ignition likelihood estimation

Table X.1 Linking probability ranges with the frequency of occurrence

Ignition Likelihood	**Frequency of Occurrence Assessment for Ignition Sources** (EN 13463-1, 2009)	**Probability of Explosive Atmosphere Formation in 365 days** (CEI 31-56, 2007; CEI 31-35, 2012)	**Area Classification**
Frequently	During normal operation	$P>10^{-1}$	Zone 0/20
Occasionally	During foreseeable malfunction	$10^{-1}\geq P>10^{-3}$	Zone 1/21
Rarely	During rare malfunction	$10^{-3}\geq P>10^{-5}$	Zone 2/22
N.E.	Not relevant	$10^{-5}>P$	Zone NE

X.3 Quantitative Analysis of Barrier Failure (Pr_{BF})

The applied barriers consist of technical barriers and/or operational barriers. These barriers are also characterized through a potential probability to fail (Pr_{BF}): 1) the probability of the technical barrier failure (P_{tbf}), which can be estimated by using the function analysis with the relevant technical document; 2) the probability of the operational failure (in terms of the HEP) that can be estimated by applying human reliability analysis (HRA) techniques.

Several types of methodologies are used for identifying and quantifying human error and among them are the Human Reliability Analysis (HRA). Human reliability is the probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system, such as THERP, FUZZY CREAM, and etc.

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