MultHyFuel

Deliverable 3.2

Benchmarking of Risk Assessment Methodology Applied to Refuelling Stations

Authors:
Sébastien Quesnel, Quentin Nouvelot and Bachir Idrissi Ouadghiri, ENGIE

Reviewers:
Olivier Gentilhomme, Sylvaine Pique, INERIS
Ju Lynne Saw, HSE
Alexandru Floristean, Joana Dias Fonseca, HYDROGEN EUROPE

Status: final version
Report Date: June 2021

Confidentiality Level: Public

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under Grant Agreement No 101006794. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe research.

Executive Summary

Clean Hydrogen and Fuel Cell Electric Vehicles (FCEV) have developed significantly in the past years in order to respond appropriately to the challenges associated with the transition to a net zero carbon Economy.

Associated infrastructure, in particular, Hydrogen Refueling Stations (HRS) have also developed to respond to the increasing needs for Hydrogen in the mobility sector. The need to mainstream Hydrogen in the mobility sector requires higher levels of accessibility of HRS in the public environment.

In response to these challenges, the MultHyFuel project proposes to study how hydrogen refueling stations can be relevantly and safely integrated in close proximity, alongside other conventional and alternative fuels for the H2 mobility.

Deliverable 3.2 contains a state of the art of the risk assessment methods and practices for HRS and conventional refueling stations. This state of the art will allow us to set up recommendations for MultHyFuel's project risk assessments.

Hence, in this deliverable, we first set up a description of the key concepts regarding the risk management, some risk assessment methods and the risk acceptance criteria. These key concepts allow a better understanding of the state of the art of the risk assessment conducted afterwards.

Regarding the state of the art, it is achieved in two steps, first the state of the art of risk assessment methods for HRS and then for the conventional refueling stations. In order to do so, data were collected from scientific publications, consortium members' feedback, safety reviews and reports conducted by external organizations.

These data collection allowed us to identify:

- the risk assessment methods used
- the risk criteria and representation (risk matrix/ FN curves)
- the sources used for the evaluation of leak frequencies and accidents
- the calculation methods and tools used to determine the effect distances (hazard range)
- the safety-critical scenarios
- the main safety barriers for the critical scenarios

Thanks to the data collected a statistical analysis was conducted. In order to underline what are the most used methodologies and tools for the risk assessments for hydrogen and conventional refueling stations, as well as the critical scenarios and safety barriers related. The statistical analysis showed that the risk assessment methods that are the most commonly used for hydrogen as well as for conventional refueling station are HAZID (HAZards Identification), HAZOP (HAZard and Operability) and QRA (Quantitative Risk Assessment). Regarding the modeling software, we observed that PHAST is the consequence modelling tool most frequently used for HRS and conventional fuel stations.

The common critical scenarios are leak on dispensers and storage for both types of refueling stations. In addition, catastrophic rupture of fuel delivery truck (LPG, gasoline, LNG) and leak on H2 compressor are the additional critical scenarios specific to each fuel.

In addition, thanks to the bibliographic research, we could establish a non-exhaustive list of safety barriers relating to safety critical scenarios for HRS and conventional fuel station. We can mention the safety barriers related to the loss of containment or bursting of capacity:

- crash-barrier around equipment
- pressure relief valve
- gas detectors and emergency shutdown
- Emergency Shutdown Device and shut-off valves

The previous statistical analysis led to recommendations for the following tasks 3.3 (Preliminary risk assessment) and 3.4 (Detailed risk assessment) of the MultHYfuel project.

The main recommendations for task 3.3 are:

- To divide the PFD of the configurations from deliverable D3.1 into sub systems.
- To select a representative environment/lay out for each configuration.
- To pre-determine the range of severity with a H2 quick evaluation tool to help with ranking of the severity of the H2 scenarios.
- To pre-determine the range of frequencies of typical leaks or rupture scenarios related to H2 equipment identified as the mostly mentioned in safety critical scenarios.
- To conduct a HAZID exercise on the configurations identified in deliverable D3.1
- To use a Rapid Risk Ranking matrix in order to assess the identified risks and to take into consideration the environment/lay out for each configuration.
- Define risk acceptance criteria and rank the scenarios plotted on the risk matrix in order to identify the higher risk scenarios to be studied in task 3.4 (Detailed risk assessment).

The main recommendations for task 3.4 are:

- Achieve a specific review of the data available for the likelihood evaluation.
- Evaluate the frequencies thanks to the database selected by the review.
- Compare the safety distances using different consequence modelling tools in order to evaluate the potential severity of these scenarios (impact on humans & equipment) and to validate the tools used for safety distances.
- Evaluate the consequence with and without safety barriers.
- Analyse the domino effects between hydrogen dispenser and other fuel dispensers in the multifuel context for each configurations defined in task 3.1 (state of the art about technologies).

Content

Acronyms

ALARP	As Low as Reasonably Practicable
BLEVE	Boiling Liquid Expanding Vapor Explosion
CFD	Computational Fluid Dynamics
CNG	Compressed Natural Gas
DNV	Det Norske Veritas
EI	Energy Institute
ESD	Emergency Shutdown Device
ESS	Emergency Shutdown System
EV	Expectation Value
FLACS	FLame ACceleration Simulator
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effect and Criticality Analysis
HAZID	HAZard IDentification
HAZOP	HAZard and OPerability
HRS	Hydrogen Refueling Station
HSE	Health and Safety Executive
HyRAM	Hydrogen Risk Assessment Model
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
OREDA	Offshore & onshore reliability data
PFD	Process Flow Diagram
PHAST	Process Hazard Analysis Software Tool
P&ID	Piping and Instrumentation Diagram
PLL	Potential Loss of Life
QRA	Quantitative Risk Assessment
RI	Risk Integral
SIF	Safety Instrumented Function
SRD	Safety and Reliability Directorate
UKOOA	United Kingdom Offshore Operators Association

Table of figures

1 Background and context

The main goal of WP3 is to **develop best practice guidelines that can be utilized as a common approach to risk assessment** (e.g. related to leak scenarios to be considered, important fault tree analysis paths to be considered, potential consequences and hazard ranges of different types of leaks, suggested methodologies for risk modelling and potentially hazardous area classification such as definition of zones 0/1/2, separation distances, etc.) for **addressing the safe design of hydrogen refueling stations in a multi-fuel context.**

Using appropriate **risk assessment techniques, combined with the data provided by WP2** (expected likelihood and consequence, ignition frequency in a forecourt environment with limited control over the presence of potential ignition sources), risks will be assessed, considering the additional control/mitigation methods that could be anticipated to be used in hydrogen dispensers.

WP3 will investigate whether or not any of these measures should be recommended, and if any of the measures have a preference to be used over others. This WP will be realized through the following steps:

✦ Task 3.1 - State of the art study about technologies to define configurations of HRS in multifuel context (deliverable D3.1 published on the MultHyfuel website);

✦ Task 3.2 - **Benchmark of risk assessment methodologies used on refueling stations (**this deliverable D3.2) in order to recommend tools and methods related to risk assessment for the next tasks;

✦ Task 3.3 - Preliminary risk assessment on previous configurations to identify the potential critical scenarios. The most suitable risk assessment method identified in the previous task 3.2 will be applied on the configurations identified in the task 3.1;

✦ Task 3.4 - Detailed risk assessment on scenarios identified during the preliminary risk assessment (task 3.3) to evaluate the severity and likelihood of these scenarios.

✦ Task 3.5 – Identify and confirm the critical scenarios, equipment and safety barriers to be studied in experimental WP2 thanks to the detailed risk assessment results.

✦ Task 3.6 - Review of the previous critical scenarios with the inputs of WP2 (experimentations) in order to to define separation distances and requirements of safety barriers for the safe implementation of HRS in a multifuel context.

✦ Task 3.7 - Drafting best practice guidelines for multi fuels stations will be based on the WP3 findings to be used as a recommendation for standards development (deliverable D3.7 to published on the website at the end of the project)

2 Introduction to the report

This document is part of the study framework of the European project MultHyFuel. The main objective of Work Package 3 is to formulate best practice guidelines on what constitutes safe design(s) for hydrogen refueling stations (HRS) in multi-fuel context.

In this document, we present the current state of the art of risk assessment methods for HRS and conventional refueling stations in order to establish recommendations on the best risk assessment approach to be used for the next steps of the project.

In order to do so, we will first define what constitutes a risk assessment and then describe the methodologies most commonly used for refueling stations (see Section 3).

Following this, in order to present the state of the art of risk assessment for HRS, we will specify:

- the risk assessment methods used (sections 4.2)
- the risk criteria and representation (risk matrix/ FN curves) (section 4.3)
- the sources used for the evaluation of leak frequencies and accidents (section 4.4)
- the calculation methods and tools used to determine the effect distances (hazard range) (section 4.5)
- the safety-critical scenarios (section 4.6)
- the main safety barriers for the critical scenarios that should be considered to ensure ALARP (section 4.7)

Additionally, the same structure will then be used for conventional refueling stations (section 5). Finally, we will synthesize and analyze the results obtained for both hydrogen and conventional fuel refueling stations (section 6) in order to make recommendations on a common and consistent risk assessment method to apply for multi-fuel stations (section 7).

3 Introduction to basic risk assessment definitions

In this chapter the risk management and risk assessment principles will be described and the main risk assessment methodologies (What if, HAZOP, will be introduced.

3.1 Risk management

According to the ISO 31000:2018 - Risk management - Guidelines [1] an effective risk management requires the organization (e.g. a company, a corporation, an institution) to follow the requirements presented in Table 1:

Table 1 - Requirements for an effective risk management [1].

The organization should be :	Explanation
Integrated	Risk management is an integral part of all organizational activities.
	A structured and comprehensive approach to risk management contributes to consistent and comparable results.
Customized	The risk management framework and process are customized and proportionate to the organization's external and internal context related to its objectives.
	Appropriate and timely involvement of stakeholders enables their knowledge, views and perceptions to be considered. This results in improved awareness and informed risk management.
Dynamic	Risks can emerge, change or disappear as an organization's external and internal context changes. Risk management anticipates, detects, acknowledges and responds to those changes and events in an appropriate and timely manner.
Having the best available information	The inputs to risk management are based on historical and current information, as well as on future expectations. Risk management explicitly takes into account any limitations and uncertainties associated with such information and expectations. Information should be timely, clear and available to relevant stakeholders.
Considering the human and cultural factors	Human behaviour and culture significantly influence all aspects of risk management at each level and stage
	Risk management is continually improved through learning and experience

Once these principles are implemented within the organization, the organization can be said to be also setting up a framework of leadership and commitment. According to [1] in order to stay in this framework, the risk management should be subject to requirements presented in Table 2:

Table 2 - Requirement for the organization to be in a framework of leadership and commitment [1].

The risk management should be subject to:	Explanation
Integration	Making sure that the risk management is part of the organization's governance and that everyone in the organization has a responsibility of managing risks
Design	When designing the framework for managing risk, the organization should examine and understand its external and internal context.
Implementation	It will ensure that the risk management process is a part of all activities throughout the organization, including decision-making, and that changes in external and internal contexts will be adequately captured
Evaluation	By periodically measuring the performance of the risk management framework and determine whether it remains suitable to support achieving the objectives of the organization
Improvement	By continually monitoring and adapting the risk management framework to address external and internal changes.

Risk management is an important process whether in the industrial or non-industrial field. This process allows the evaluation and the treatment of risks related to an installation or an activity.

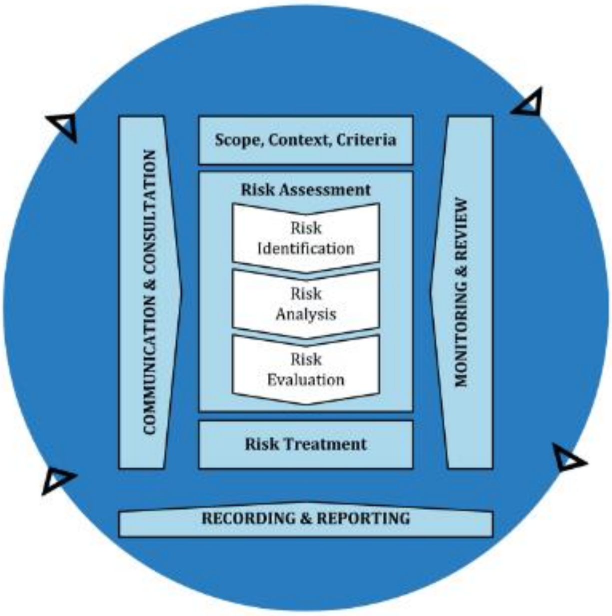


Figure 1 : Representative diagram of the risk management process [1]

As it is shown in Figure 1, the risk management process consists of many iterative steps.

The first step of the process is the **communication and consultation** [1] with the relevant stakeholders so that different areas of expertise are brought together for the risk management process. The creation of such a working group will allow the risk criteria and evaluation to be based on different points of view due to the breadth of information offered. Also, this step of the process makes the risk oversight and the decision-making easier since it includes those who might be affected by the risks.

The next step of the process is to customize the risk management process by establishing the **scope, the context and the risk criteria** [1] so that its assessment and treatment are effective. The risk criteria (defined in Section 3.4 and 4.3 as "Risk acceptance criteria") will be used to assess whether the identified risks are acceptable or not.

Thus, the scope of the risk management process allows the organization to consider:

- the outcomes expected from the process;
- the objectives and decisions to make;
- the resources required and the responsibilities and the records to be kept;
- the appropriate risk assessment tools and techniques.

Once the scope is defined, the external and internal context of the process should be established in order to identify the environment within which the organization is going to achieve its objectives [1]. Then, the organization must define the risk criteria that reflects its values, objectives and resources while considering its obligations as well as the views of the stakeholders.

Hence, according to ISO 31000:2018 - Risk management - Guidelines [1], the organization should consider the following to **set up the risk criteria**:

- the nature and type of uncertainties that can affect the outcomes and objectives;
- how the consequences and likelihood will be defined and measured/ estimated;
- how the level of risk is to be determined;
- how the combinations and sequences of multiple risks (including domino/ escalation effects) will be taken into account;
- consistency in the use of measurements;
- time related factors;
- the organization's capacity.

Once the risk management process is well customized, the risk assessment can be carried out by identification, analysis and evaluation of the risks. The risk assessment will be explained in detail in Section 3.2.

The following step of the risk management is the monitoring and review of the risk management system [1]. This step ensures and improves the quality and effectiveness of process design, implementation and outcomes since ongoing monitoring and periodic review of the risk management process and its outcomes should be planned as part of the risk management process. In reality, this task should take place in all the stages of the process since it includes planning, gathering and analyzing information, recording results and providing feedback.

The final step of the risk management process is the recording and reporting of the outcomes [1]. This task aims to communicate the risk management activities and outcomes across the organization and to provide information for decision-making. Moreover, the recording and reporting will improve risk management activities and assist interaction with stakeholders, including those with responsibility and accountability for risk management activities.

3.2 Risk assessment

As shown in Figure 1, risk assessment is an important part of the overall risk management procedure, and its main activities are the following:

- Identify the risks;
- Analyse the risks;
- Evaluate the risks.

For the **risk identification step**, according to [1], the organization should consider:

- tangible and intangible sources of risk;
- **causes and events**;
- threats and opportunities;
- **vulnerabilities** and capabilities;
- changes in the external and internal context;
- indicators of emerging risks;
- **the nature and value of assets and resources**;
- **consequences** and their impact on objectives;
- limitations of knowledge and reliability of information;
- time-related factors;
- biases, assumptions and beliefs of those involved.

According to [1], when the risk identification is carried out, **risk analysis** can be conducted. To do so, the followings elements should be taken into account:

- the **likelihood** of events and their consequences;
- the nature and magnitude of **consequences;**
- the complexity and connectivity of the risks;
- the time-related factors and volatility;

- the effectiveness and reliability of existing **controls;**
- the sensitivity and confidence levels.

Nevertheless, depending on the objective of the risk assessment and the design phase during which it takes place, the level of available information is different. Thus the risk assessment will be more or less complex: risk assessment methods can be quantitative, qualitative or a combination of both depending on the circumstances and the intended use. Moreover, depending on the project phase during which the risk assessment is carried out, different methods are used. The main risk assessment methods used for HRS and conventional stations are defined thereafter.

To illustrate the choice of risk assessment method, in the UK and France, there is "Proportionality" concept. For example, in UK, as part of COMAH (Enactment of Seveso Directive) this underlying concept is very important because it determines the level of detail required in the (1) risk assessment by the operator, (2) the demonstration by the operator; and (3) the assessment of this demonstration by the regulator.

All the following elements should be proportional to the scale and nature of the hazards at a particular installation (Proportionality is mostly driven by the consequences and severity of the hazards rather than the risk):

- Severity of the worst case event;
- Scale, nature, properties of hazards;
- Location;
- Surrounding populations (internal, external, sensitive, environmental sensitive receptors);
- Risk/ distance profiles;
- Escalation potential;
- Criticality of safety measures especially for dominos effects in a multifuel context.

After the risk assessment is completed, the results are used to decide whether the risk needs to be treated or not in the **risk evaluation** step. To evaluate the risk, we need to compare the results of the risk assessment to the risk acceptance criteria established at the beginning of the risk management process. This way, a decision can be taken to act on the risk if it is required.

Once the risk evaluation is established, the risk assessment step is completed and the risk treatment step needs to be completed, representing the **risk mitigation** process. The goal is to select and implement options for addressing the risk [1]. To do so, it is first necessary to formulate and select the most appropriate risk treatment options in order to address the risks. This involves balancing the benefits against the costs, effort or disadvantages of the implementation of the risk treatment option. Then it needs to be planned and implemented. Once it is implemented, that treatment's effectiveness needs to be assessed in order to decide whether the remaining risk is acceptable or not. If not, further treatment needs to be taken.

In order to better understand the risk management process, it is necessary to learn about the different methods of risk assessment already being used. Thus, the different risk assessment methods used for hydrogen refueling stations (HRS) and conventional stations are presented in the following Section 3.3.

3.3 Definition of risk assessment methodologies

In this section are defined the risk assessment methodologies that will be mentioned in the following sections of the report. The methods are the following:

- What-if
- Hazard Identification (HAZID)
- Failure Mode and Effects Analysis (FMEA)
- Hazard and Operability (HAZOP)
- Quantitative Risk Assessment (QRA)

3.3.1 What if

The “What if” method is focused on the consequences of the events and proposes improvement actions to be undertaken. It is therefore considered to be a qualitative risk assessment method.

In addition, this method is based on a succession of questions like the following: «What if this parameter or the behavior of this component is different from what is expected?»

In order to perform a “What if” study the working group should be composed of experienced actors since this methodology is not based on lists of pre-established keywords. The efficiency of this method is directly linked to the experience of the working group. The following figure describes the “What if” study methodology.

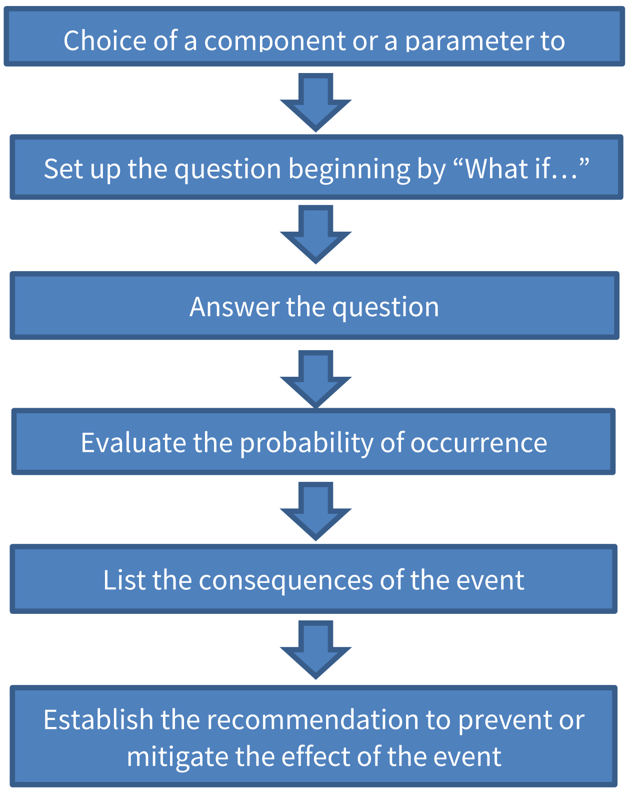


Figure 2 - The “What if” study procedure

Thus, it is useful to use a table such as the one below to group the information and results of the working group.

What if … ?	Answer	Probability of occurrence	Consequences	Recommendations

Table 3 : Example of table for the "What if" methodology [2]

The technique can be applied to systems, plant items, procedures and organizations generally. In particular, it is used to examine the consequences of changes and the risk thereby altered or created. Both positive and negative outcomes can be considered. It can also be used to identify the systems or processes for which it would be worth investing the resources for a more detailed HAZOP or Failure Modes and Effects Analysis (FMEA) [3]. This method:

- needs a clear understanding of the system, procedure, plant item and/or change and the external and internal contexts is needed;
- is established through interviews, gathering a multifunctional team and through the study of documents, plans and drawings by the facilitator;
- Is not as comprehensive as a HAZOP, potentially.

The **main output** is a register of risks with risk-ranked actions or tasks that can be used as the basis for an action plan.

The **strengths and limitations** are presented in the table below from [4]:

Strengths	Limitations
It is widely applicable to all forms of physical plant or system, situation or circumstance, organization or activity.	If the workshop team does not have a wide enough experience base or if the prompt system is not comprehensive, some risks or hazards might not be identified.
It needs minimal preparation by the team.	The high-level application of the technique might not reveal complex, detailed or correlated causes.
It is relatively rapid and the major risks and risk sources quickly become apparent within the workshop session.	Recommendations are often generic, e.g. the method does not provide support for robust and detailed controls without further analysis being carried out.
The study is "systems orientated" and allows participants to look at the system response to deviations rather than just examining the consequences of component failure.	
It can be used to identify opportunities for improvement of processes and systems and generally can be used to identify actions that lead to and enhance their probabilities of success.	

Involvement in the workshop by those who are accountable for existing controls and for further risk treatment actions reinforces their responsibility.	
It creates a risk register and risk treatment plan with little more effort.	

Table 4 : Strengths and limitations of "What If" Approach

To conclude, the key points to consider regarding the ''What If'' method, are:

- Qualitative method;
- Few inputs required;
- Identifies main hazards of the project;
- Results are strongly dependent on experience of the working group;
- Non-exhaustive review of process hazards.

3.3.2 HAZID

According to [3], HAZID (HAZard IDentification) makes it possible to identify risks at the preliminary stage of the design of a facility or project. Generally speaking, hazardous elements are:

- substances, dangerous preparations;
- equipment;
- dangerous operations;
- hazardous equipment in the vicinity able to generate domino effects.

In order to carry out a HAZID study, usually the **working group** consists of:

- Chairman
- Project manager
- Production manager
- Chemical or process engineer
- Maintenance engineer if needed
- Providers of equipment if needed
- HSE engineer

According to ISO 17776 - Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations, [5], the **main inputs** for the HAZID study are the following:

- At least a Process Flow Diagram (PFD) or a Piping & Instrumentation Diagram (PID);
- A plant or installation layout with the environment;
- A description of the installation/project and operations;
- Details of the inventories of hazardous materials;
- A list of hazardous equipment able to generate domino effects;
- Safety distances and duration of dangerous phenomena of equipment installed in the vicinity of hydrogen installations.

The above list should be completed by an analysis of the lessons learned regarding the installation and information regarding neighboring structures and facilities.

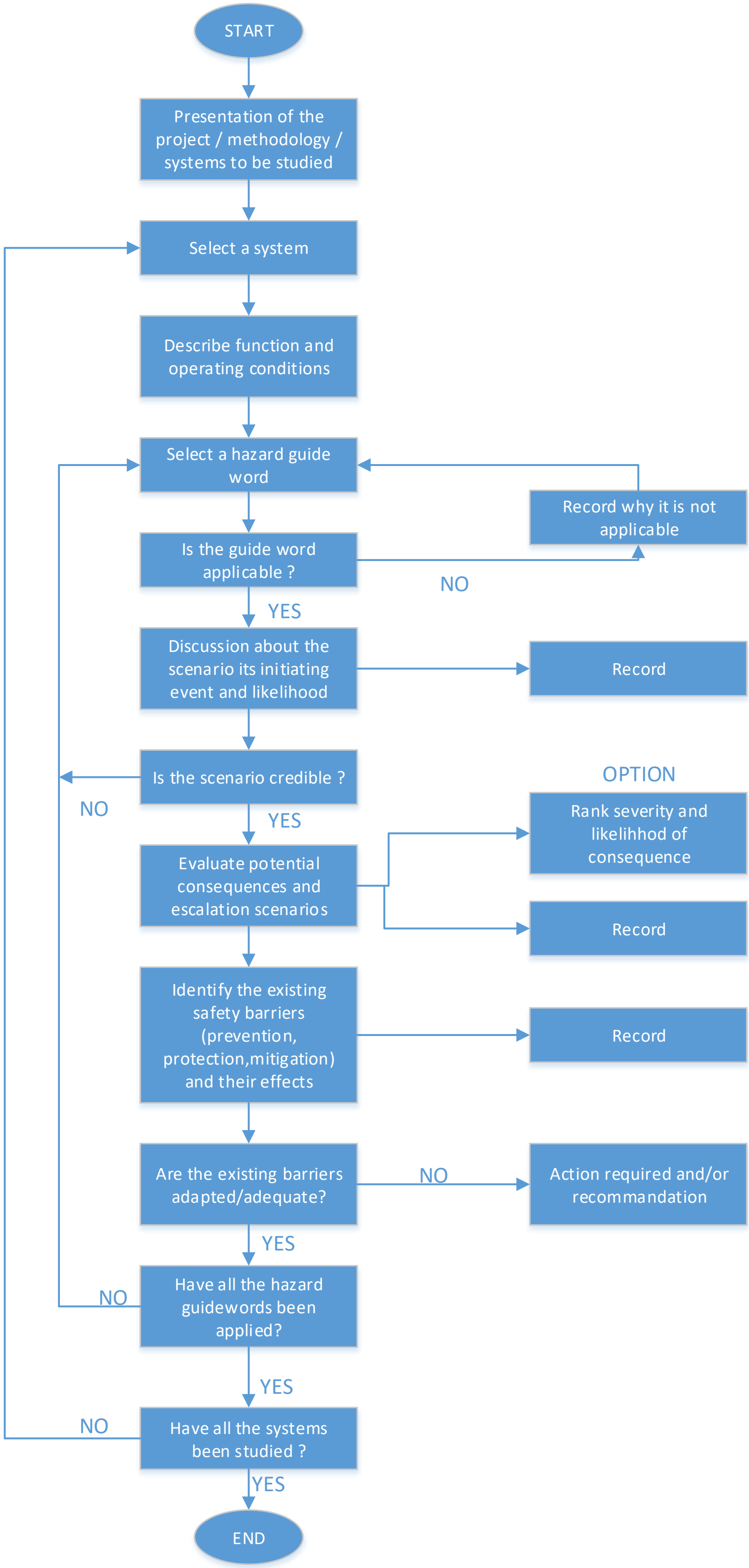


Figure 3 : The HAZID study procedure

As seen from Figure 3, HAZID allows the identification for each hazardous element of one or more hazardous situations. These hazardous situations are in fact uncontrolled situations that can lead to the exposure of issues to one or more hazardous phenomena. It is a qualitative risk assessment method, or the precursor, a starting point of a fuller risk assessment process.

The working group must then determine the **causes and consequences** of each of the hazard situations identified, and identify the **existing safety features** of the system under study. If there is no existing safety barriers identified for a scenario with safety consequences or if the working group identifies usual safety barriers that could be added to improve risk management, **suggestions for improvement** must be considered.

The table below can be used to consolidate the information from the working group's discussions.

Function or system :						**Date :**	
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
N°	**Product or equipment**	**Hazardous situation**	**Causes**	**Consequences**	**Existing safety barriers**	**Suggestions for improvement**	**Observations**
1	*Compressor*	*Natural hazard : lightning*	*Lightning strike*	*Ignition of vent releases during distribution*	*Limitation of release.*	*Study if it is necessary to stop the distribution in case of lightning.*	-
2	*Compressor*	*Natural hazard : Snow and glaze*	*Accumulation of snow*	*Obstruction of the vents and ventilation outlets*	*Ventilation outlets on side face. No flat side in the design of the vent.*	*Check the design regarding snow and rain accumulations*	-

Table 5 : Example of table for the HAZID [2]

As shown in Table 5 above, the working group will need to realize the following procedure to achieve an HAZID [2]:

- Select the system or process to be studied on the basis of the functional description performed;
- Choose an equipment or product for this system or process;
- Consider each hazardous situation (including natural hazards triggering technological disasters and/or domino effects);
- Consider all the causes and consequences for this dangerous situation;
- Evaluate the consequences from each hazards in order to help prioritizing the events that need to be analyzed in details (modelling of consequences, credibility of causes studied);
- Identify the existing safety barriers on the installation to avoid this dangerous situation;
- If the identified risk is deemed unacceptable, make proposals for improvements and specify the observations made by the team members;
- Once all the pairs of causes and hazard situations have been studied for a piece of equipment or function, we move on to the next piece of equipment;

- Once all the equipment in the system has been studied, the next system will be used.

Hence, HAZID can be used to identify equipment or installations requiring a more detailed hazard study, particularly from a process point of view. HAZID should be carried out throughout the life cycle of any installation, but is particularly important in the early stages of design so that practicable hazards can be eliminated through the application of Inherent Safety Design principles [5] .

The main **outputs of HAZID** are the followings:

- A report of every HAZID session carried out by the working group with tables;
- An early identification and assessment of the main risks related to the installation in its environment;
- A list of the safeguards implemented;
- Recommendations of additional safeguards to reduce the likelihood of hazards occurrence or to mitigate the potential consequences.

The **strengths and limitations** of HAZID methods are presented in Table 6 from [4]:

Strengths	Limitations
They promote a common understanding of risk among stakeholders.	Their use is limited in novel situations where there is no relevant past history or in situations that differ from that for which they were developed
When well designed, they bring wide ranging expertise into an easy to use system for non-experts.	They address pre-established hazardous situations
Once developed they require little specialist expertise.	Complexity can hinder identification of relationships (e.g., interconnections and alternative groupings).
	Lack of information can lead to overlaps and/or gaps (e.g. schemes are not mutually exclusive and collectively exhaustive).
	They can encourage "tick the box" type of behavior rather than exploration of ideas.

Table 6 : Strengths and limitations of Hazid

To conclude, the **key points** to consider regarding the ”Hazid” method are:

- Qualitative method;
- Few inputs required (e.g. preliminary lay out and Process Flow Diagram);
- Identifies main hazards and helps prioritization of hazardous scenarios to be studied;
- Part of a safety concept for new project (preliminary or basic studies for project)
- Exhaustive review of non-process hazards (e.g. natural hazards or domino effects due to the environment of the project)
- Non exhaustive review of process hazards

3.3.3 FMEA and FMECA

According to IEC 31010 - Risk management - Risk assessment techniques [4], FMEA (Failure Mode and Effects Analysis) can be applied during the design, manufacture or operation of a physical system to improve design, select between design alternatives or plan a maintenance program. It is a method which can be applied as a first step to study the reliability of a safety barrier as recommended by CEI 61508 [6] or CEI 61511 [7].

In addition, when it is necessary to assess the criticality of a failure, FMEA involves a semi-quantitative assessment of criticality using the probability and severity of the failure. The method is then called Failure Modes, Effect and Criticality Analysis (FMECA). Hence, it is necessary to establish a risk matrix describing the scales of probability and severity of a failure.

Moreover, INERIS [3] mentions this risk assessment method as a method allowing:

- The evaluation of the effects and the sequence of events caused by each failure mode of the components of a system on the various functions of this system.
- The determination of the importance of each failure mode on the normal operation of the system and assess the impact on the reliability and safety of the considered system.
- To prioritize the known failure modes according to the ease of detection and treatment.

Thus, in order to perform a FMECA study the **working group** should be composed of:

- Project manager or designer
- Production manager
- Instrument engineer
- Maintenance engineer
- Quality Control engineer

The following figure describes the FMECA study methodology.

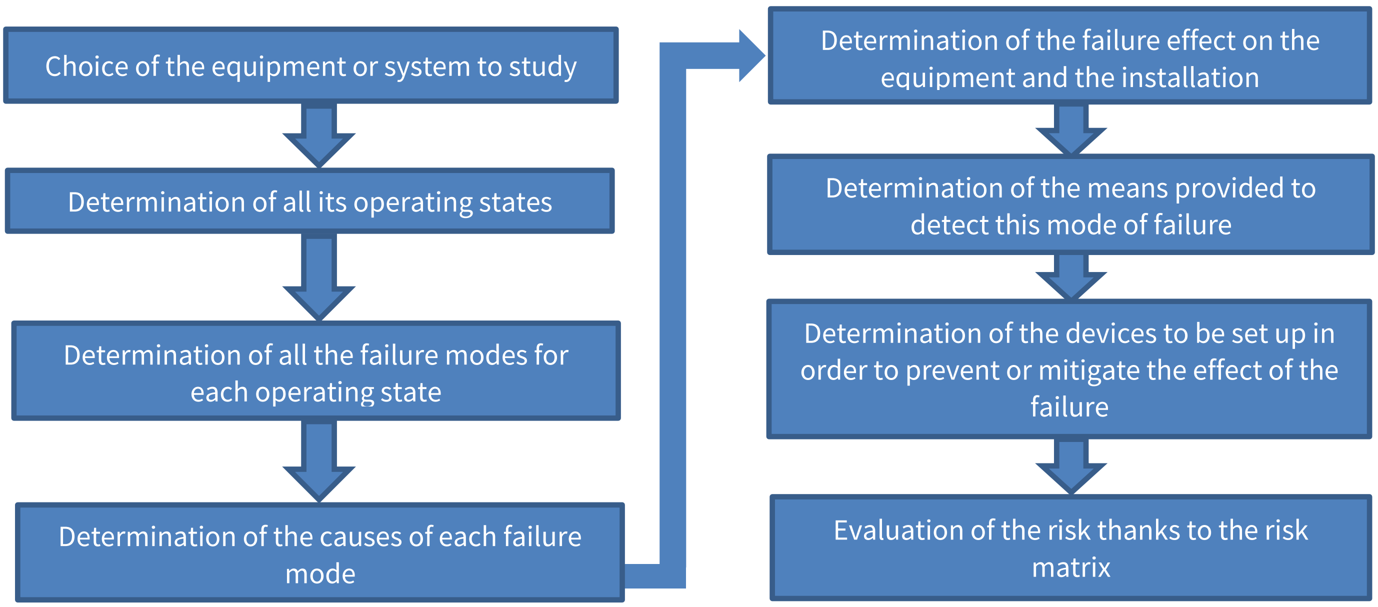


Figure 4 : The FMECA study procedure

According to [3], the **main inputs** include:

- information about the system to be analyzed and its elements in sufficient detail for meaningful analysis of the ways in which each element can fail and the consequences if it does;
- drawings and flow charts;
- details of the environment in which the system operates;
- historical information on failures where available.

A table such as the one below is useful to group the information and results of the working group.

1	2	3	4	5	6	7	8	9	10	11
Equipment Reference	**Function, states**	**Failure mode**	**Cause of the failure**	**Local effect**	**Final effect**	**Detection means**	**Compensatory provisions**	**P**	**G**	**Comments**
FCV-103 (Pump inlet valve)	*Controls storage tank flow to pressure tank*	*Fail to transfer position*	*Bad signal, mechanical fault, or environment condition of the valve (ice)*	*yes*	*Lose flow from storage tank to pressure tank*	*Initial choice of valve, routine inspection and preventive maintenance*	*N/A*	*1*	*3*	
		Fails to remain open/plugs	*Mechanical fault Loss of power Foreign material*	*yes*	*Cannot pump LNG on demand*	*Inspect and maintain*	*N/A*	*1*	*2*	
		External leak	*Steam leak Valve body crack*	*yes*	*Depressurization of pump inlet line, release gas to environment*	*Sensors to detect gas release*	*N/A*	*2*	*3*	
		Fail to control flow	*Bad signal, mechanical fault or ice buildup*	*yes*	*Flow may decrease or increase, pressure may fluctuate*	*Monitor pressure in both tanks*	*N/A*	*1*	*3*	

Table 7 : Example of table for the FMECA [3]

In order to fill in Table 7, it is first necessary to select a piece of equipment in the installation and determine all its operating states. Then, for each operating state, the possible failure modes must be considered, taking into account the following:

- Uses of the system;
- Characteristics of the equipment considered;
- The mode of operation;
- Operational specifications;
- The cinetic of failure;
- The environment.

For example, a failure mode can be a leakage, a valve being stuck or an operation failure. Then, for each failure mode considered, the potential causes leading to this failure mode must be identified. In addition, it will be necessary to consider the possible failures on neighboring equipment. The working group will therefore have to examine the effects and consequences of the failure on the equipment in question as well as on the installation as a whole. It will then be necessary to determine the means provided to detect this mode of failure as well as the devices to be put in place at the time of the design of the installation in order to prevent or mitigate the effect of the failure.

Finally, the working group will have to estimate the probability of the failure mode (P) as well as the severity associated with its consequences (G) [3] by using the pre-established risk matrix (see Section 4.3 for examples).

The **outputs** of FMEA are [3]:

- a worksheet with failure modes, effects, causes and existing controls;
- a measure of the criticality of each failure mode (if FMECA) and the methodology used to define it;
- any recommended actions, e.g. for further analyses, design changes or features to be incorporated in test plans.

The **strengths and limitations** are presented in the table below from [4]:

Strengths	Limitations
It can be applied widely to both human and technical modes of systems, hardware, software and procedures.	FMEA can only be used to identify single failure modes, not combinations of failure modes.
It identifies failure modes, their causes and their effects on the system, and presents them in an easily readable format.	Unless adequately controlled and focused, the studies can be time consuming and costly.
It avoids the need for costly equipment modifications in service by identifying problems early in the design process.	FMEA can be difficult and tedious for complex multi-layered systems
It provides input to maintenance and monitoring programs by highlighting key features to be monitored.	

Table 8 : Strengths and limitations for FMEA

To conclude, the **key points** to consider regarding the FMEA method are:

- Difficult to apply for complex system;
- Powerful for maintenance plan definition but less adapted to safety studies;
- Requires failure mode knowledge and specialists of the technologies involved.
- It is a qualitative risk assessment methodology and can become semi-quantitative if the criticality of a failure is assessed (FMECA).

3.3.4 HAZOP

According to IEC 31010 [4], HAZOP studies were initially developed to analyze chemical process systems, but have been extended to other types of system including mechanical, electronic and electrical power systems, software systems, organizational changes, human behavior and legal contract design and review. Moreover, it is considered to be structured and systematic examination of a planned or existing process, procedure or system that involves identifying potential deviations from the design intent, and examining their possible causes and consequences. HAZOP is therefore considered to be a qualitative risk assessment method.

According to [4], in order to carry out a HAZOP study, the **working group** consists of:

- An experience leader or facilitator of the HAZOP study
- Designers (i.e. process engineer)
- Operators of the system
- HSE engineer
- Providers of equipment

Additional persons could also participate to bring their expertise (e.g. process control engineer, corrosion expert, technology expert)

Furthermore, the IEC 31010 - Risk management - Risk assessment techniques [4] mentions the **main inputs** for the HAZOP study as the following:

- Drawings
- Specification sheets
- Flow diagrams
- Process control and logic diagrams
- Piping and Instrumentation Diagram (P&ID)
- Operating and maintenance procedures

The HAZOP method is thus a method that requires the examination of fluid flow diagrams and plans and P&ID (Piping and Instrumentation Diagram) diagrams [3], since the method focuses on identifying and analyzing the risks related to the installation's process. Moreover, the flow diagrams are divided in systems called nodes which includes different equipment with same operating conditions.

The following figure describes the HAZOP study methodology.

Definition

- Initiate the study
- Define scope and objectives
- Define roles and responsibilities

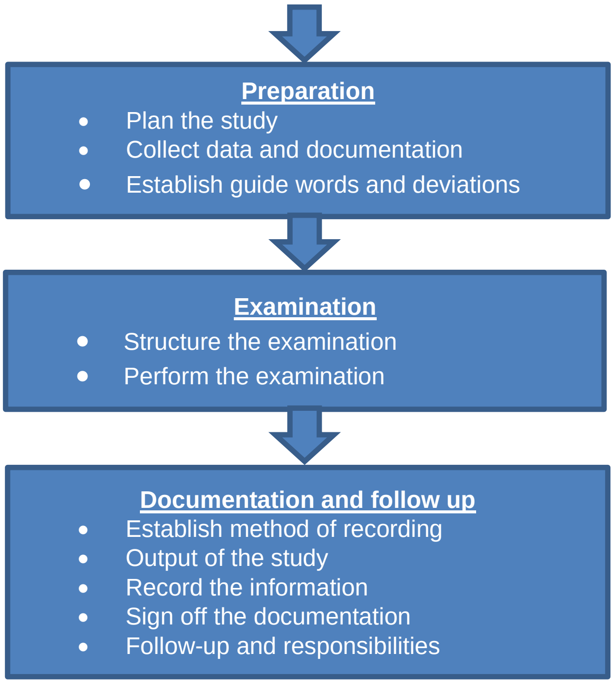


Figure 5 : HAZOP study methodology [8]

Thus, one of the tools used for the HAZOP study is the table below to guide the reflection and collect the results of the discussions carried out within the working group.

STUDY TITLE : ***Process example***	**SHEET :** ***1 of X***	
Drawing No. :	**REV No. :**	**DATE:** *December 17, 1998*
TEAM COMPOSITION :	*LB, DH, EK, NE, MG, JK*	**MEETING DATE :** *December 15, 1998*
PART CONSIDERED :	*Transfer line from supply tank A to reactor*	
DESIGN INTENT :	**Material :** A	**Activity :** *Transfer continuously at a rate greater than B*
	Source : *Tank A*	**Destination :** *Reactor*

No.	Guide word	Element	Deviation	Possible causes	Consequences	Existing controls	Comments	Actions required	Action allocated to
1	*NO*	*Material A*	*No material A*	*Supply tank A is empty*	*No flow of A into reactor Explosion*	*None shown*	*Situation nor acceptable*	*Consider installation on tank A of a low-level alarm plus a low level trip to stop pump B*	*MG*
3	*MORE*	*Material A*	*More material A : supply tank over full*	*Filling of tank from tanker when insufficient capacity exists*	*Tank will overflow in bounded area*	*None shown*	*Remark : This would have been identified during examination of the tank.*	*Consider high-level alarm if not previously identified*	*EK*

Table 9 Example of HAZOP study given in the IEC 61882:2016 standard [8]

In order to fill in Table 9Table 9 Example of HAZOP study given in the IEC 61882:2016 standard it is first necessary to define the list of keywords that can be entered in column 2. These keywords will then be used to systematically generate the drifts to be considered. Thus, the table below presents a list of examples of keywords proposed by the IEC 61882 - Hazard and operability studies (HAZOP studies) - Application guide [8].

Type of deviation	Key word	Examples of interpretations
Negative	NOT TO DO	No part of the intent is fulfilled
Quantitative modification	MORE	Quantitative increase
	LESS	Quantitative decrease
Qualitative modification	IN ADDITION TO	Presence of impurities - Simultaneous execution of another operation/step
	PART OF	Only part of the intention is realized
Substitution	INVERSE	Applies to the reversal of flow in pipelines or the reversal of chemical reactions
	OTHER THAN	A result different from the original intention is obtained

Time	EARLIER	An event occurs before the scheduled time
	LATER	An event occurs after the scheduled time
Sequence order	BEFORE	An event occurs too early in a sequence
	AFTER	An event occurs too late in a sequence

Table 10 : Examples of keywords for HAZOP [5]

Once the keywords have been defined, the parameters to which they will be linked must be defined. These parameters are chosen according to the system being studied and the impact on the security of the installation. According to [3] the following parameters are frequently found:

- Temperature,
- Pressure,
- Flow rate,
- Level,
- Concentration,
- Agitation,
- Quantity,
- Absorption,
- Composition,
- Separation,
- Homogeneity,
- Viscosity

Moreover, start up and shutdown phase can be assessed during HAZOP in order to check if these phases could generate additional risks not already covered by the analysis of parameters during normal operation. Once all the disturbances have been set up using the keywords and associated parameters, it is necessary to determine the deviations, the causes and consequences of each drift in order to complete Table 9.

Finally, the HAZOP identifies, for each deviation, the existing controls and safety barriers planned to reduce its occurrence or effects. If the measures put in place seem insufficient in view of the risk involved, the working group can propose improvements to mitigate these problems or at least define actions to be taken to improve safety on these specific points. Moreover, the set-up actions are assigned to members of the HAZOP team composition.

According to [4] the **main outputs** of the HAZOP study are the following:

- A report of the HAZOP meetings with deviations for each review point recorded;
- For each deviation, a description of the scenario with the causes, consequences and safety barriers implemented;
- Actions to address the identified problems (column 8 table 3);
- The person responsible for each action.

The **strengths and limitations** of the method are presented in the table below from [4]:

Strengths	Limitations
It provides the means to systematically examine a system, process or procedure to identify how it might fail to achieve its purpose.	The discussion can be focused on detail issues of design, and not on wider or external issues.
It provides a detailed and thorough examination by a multidisciplinary team.	A detailed analysis can be time consuming and therefore expensive.
It identifies potential problems at the design stage of a process.	The technique tends to be repetitive, finding the same issues multiple times; hence it can be difficult to maintain concentration.
It generates solutions and risk treatment actions.	A detailed analysis requires a high level of documentation or system/process and procedure specification.
It is applicable to a wide range of systems, processes and procedures.	It can focus on finding detailed solutions rather than on challenging fundamental assumptions (however, this can be mitigated by a phased approach).
It allows explicit consideration of the causes and consequences of human error.	It is constrained by the (draft) design and design intent, and the scope and objectives given to the team.
It creates a written record of the process, which can be used to demonstrate due diligence.	The process relies heavily on the expertise of the designers who might find it difficult to be sufficiently objective to seek problems in their designs

Table 11 : Strengths and limitations of Hazop

To conclude, the **key points** to consider regarding the HAZOP method are:

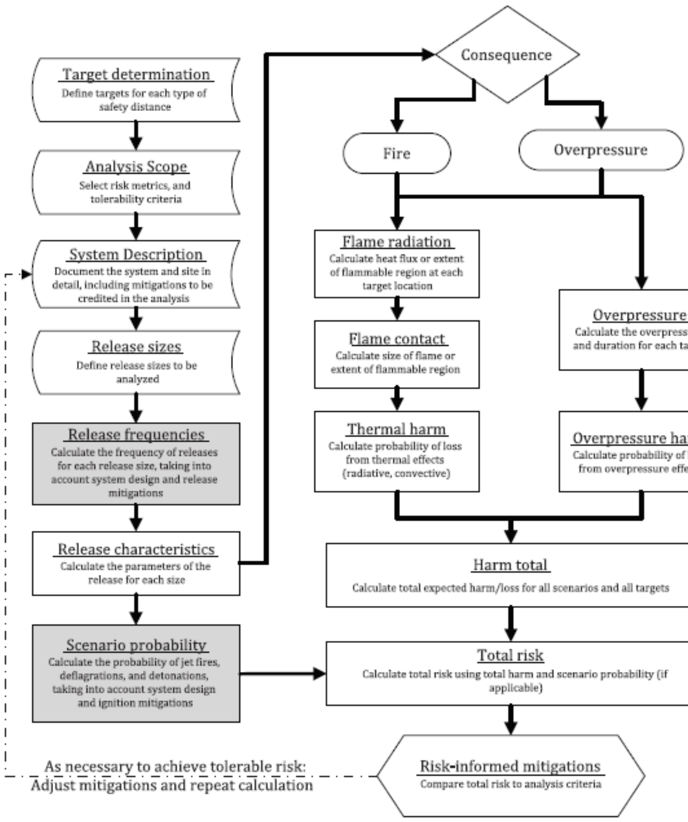
- Qualitative method;
- Advanced inputs required (e.g. PID, list of safety barriers, design specification of equipment);
- Identifies process hazards and helps the prioritization of hazardous scenarios to be studied;
- Strong link with the design phase of project (detailed studies for project);
- Non-exhaustive review of non-process hazards;
- Exhaustive review of process hazards (focus on process deviations).

3.3.5 QRA

According to BEVI [9], a Quantitative Risk Assessment (hereinafter referred to as: QRA) is used to make decisions about the acceptability of risk in relation to developments for a company or in the area surrounding an establishment or transport route. Generally, this method will complement a qualitative risk assessment (e.g. HAZID/HAZOP) if required by local regulation or if the complexity of the environment requires a quantification of the risks to evaluate the acceptability of the project.
According to INERIS [3], the Quantitative Risk Assessment is a method whose objective is to evaluate the probability of damage caused by a potential accident. The particularity of QRA methods lies in

the way in which the results of the risk assessment are expressed and represented. Individual risk and societal risk are generally calculated. Individual risk is the probability that an individual at a given location will be impacted from the effects of the accident. Societal risk is the fraction of the population likely to be impacted from the effects of the accident and the associated frequency.

Figure 6 represents an example of approach for the QRA methodology applied to separation distances in HRS.



NOTE 1 Grey shading denotes an analysis step that is used only in full-QRA approach.

NOTE 2 Concave rectangle denotes an analysis step.

NOTE 3 Rectangle denotes a calculation step.

NOTE 4 Diamond denotes branching.

Figure A.1 — Example of a risk-informed approach to safety distances

Figure 6 : Diagram of the full QRA method applied to separation distances in HRS [2]

Furthermore, according to the Purple book, [10] the main steps are the followings:

- **Selection of the facilities/ systems** for QRA [3]

  The selection of facilities is based on the calculation for each facility of an indicator that takes into account the quantity of hazardous substance stored or used, the type of equipment (storage or process), the exposure of the facility to particular conditions, the physical state of the substance and the nature of the substance. Depending on the value of the indicator, the installation is selected or not for the QRA.

- **Definition of central dreaded events** [3]

For each facility/system selected for the QRA, the method includes the listing of central dread event (e.g. potential loss of containment, bursting of a tank). These events are considered independently of their causes on the basis of a pre-established association between an equipment typology and an event typology.

- **Likelihood evaluation**

For each type of event, the Purple Book [10] associates a frequency value which is used for the probabilistic calculations that follow. These values come from statistical studies. Moreover, if additional protection or mitigation safety barriers are present to limit or mitigate the consequences of a loss of containment it is theoretically possible to take them into account by applying event tree methods. On the other hand, it is not possible to take into account specific prevention barriers that would reduce the probability of a loss of containment. Regarding HRS project, given the lack of feedback data for hydrogen and even more for the safety barriers introduced with hydrogen, it is a challenge to assess very well the probability.

- **Consequence modelling** [3]

The modeling of the consequences of the events leads to calculate the intensity of the dangerous phenomenon for each loss of containment event resulting from the previous step. The intensity is expressed thanks to the distribution of concentrations of flammable substances, the levels of heat flow or the levels of overpressure depending on the phenomenon under consideration. The models to be used are those described in the "Yellow book" [11]. These are classical thermal, dispersion and explosion effect models. The models also depend on meteorological conditions which introduce a probability of occurrence to be taken in consideration in the likelihood evaluation (e.g. wind direction for a flammable cloud).

- **Severity evaluation**

In this step, the intensities of dangerous events must be converted into the probability of injuries and/or death of an exposed individual and the fraction of the population injured and/or killed. To do this, Probit functions can be used for example. Some models used are described in the 'Purple Book' [10] and the 'Green Book' [12].

- **Calculation and presentation of results**

For this last step, it is first necessary to estimate the individual risk by summing the probabilities of death associated with each result of the event intensity modeling step. Then, the societal risk is determined by dividing the space around the facility into cells of equal size and estimating the potentially exposed population in each cell and the number of deaths among this population for each result of the event intensity modeling step. Thus, by summing the number of deaths in each cell surrounding the facility for a given scenario and a given set of conditions, we obtain the contribution in number of deaths from that scenario and data set. To establish societal risk it is necessary to set up the mortality classes and calculate the sum of the frequencies (F) of the scenarios that may produce a number greater than or equal to the number of deaths (N) in the class for each of the classes.

For example, in some countries, the **results of the QRA** can be represented in three ways:

- an individual risk contour map;
- an F/N curve;

- scenario risks [event likelihoods vs. severity (how many people are harmed)] that are then plotted on risk matrices described in Section 4.3, in order to distil out the safety critical events (SCEs) that are chosen for detailed ALARP demonstration.

In both cases, the exploitation of the results for decision-making involves defining an acceptable level of risk in terms of injury or death probability.

Below is an example of an individual risk map. This map shows the Individual Risk contours of a fictitious plant.

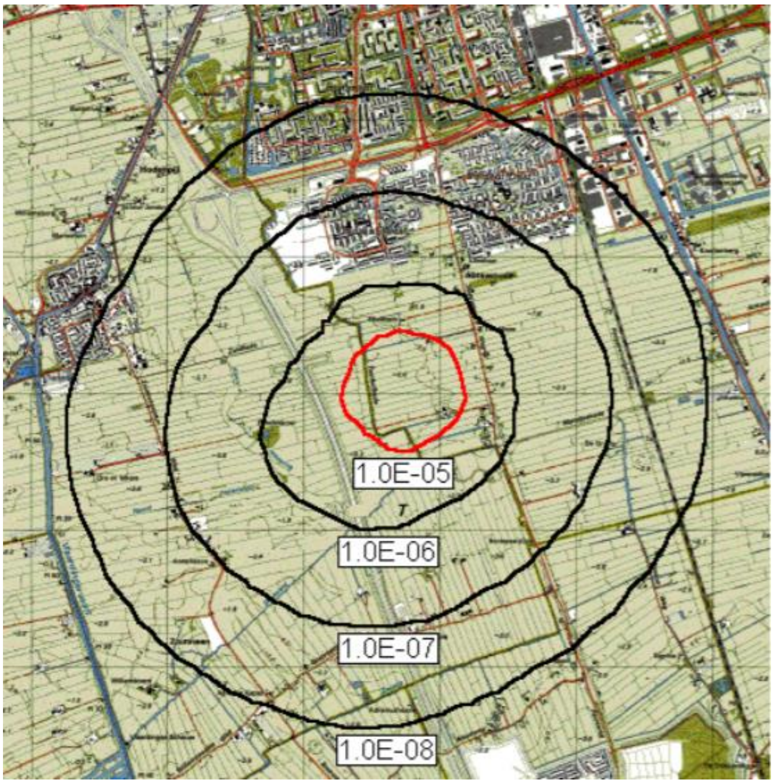


Figure 7 : Presentation of the Individual Risk map of a ficticious plant [10]

Below is an example of the F/N curve of a fictitious plant and the recommended limit for establishment.

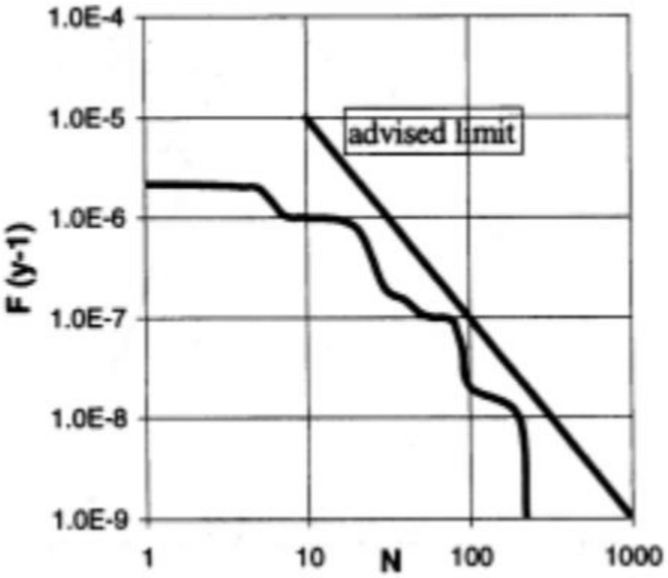


Figure 8 : Presentation of the Societal Risk curve i.e. F/N curve.

The **strengths and limitations** are presented in the table below:

Strengths	Limitations
Exhaustive review of consequences for large and small leaks to take in consideration all the hazardous events	Time and resources consuming
Express the results quantitatively as risk to people	F/N criteria and curves complexity
Useful to define the location of gas detectors Useful for the lay out of the projects regarding the impact on buildings around	Cumulative expression makes it difficult to interpret, especially by non-risk specialists

Table 12. Strengths and limitations of QRA

To conclude, the **key points** to consider regarding the HAZOP method are:

- A quantitative approach to evaluate the likelihood and consequences of hazardous events;
- Highlights the accident scenarios that contribute most to overall risk (e.g. sensibility studies).
- Useful to demonstrate that risks are acceptable or as low as reasonably practicable (ALARP) in complex environment (e.g. HRS close to public facilities)

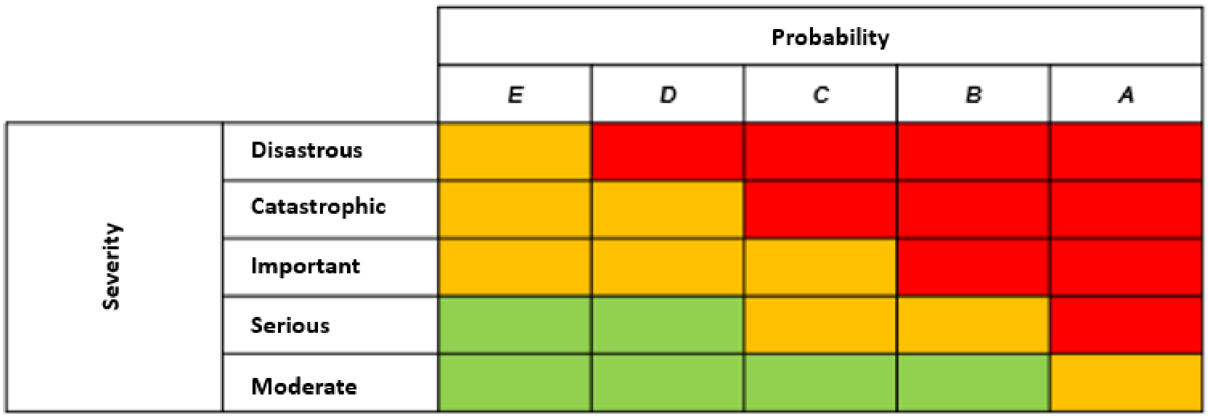
3.4 Risk acceptance criteria

The risk acceptance criteria is the parameter which allows the evaluation of risk tolerability. It is a necessary criteria for the risk assessment since it allows the working group to decide whether a risk is acceptable or not.

Depending on the risk assessment methodology, the main criteria used are:

- A **risk matrix** where the risk level of an accident is based on the combination of its severity and its probability of occurrence (e.g. used in FMECA).
- A **threshold value** as for example the individual risk which represents the risk of an (unprotected) individual dying as a direct result of an on-site accident involving dangerous substances (e.g. 10^{-6} per year is the value of the risk curve in Netherlands) (e.g. used in QRA)

Actually, the choice of the risk matrix depends on whether the risk assessment methodology is qualitative or quantitative. If it is a qualitative risk assessment method, the scales of severity and probability of occurrence (or likelihood) will be defined qualitatively as shown in Figure 9 bellow. If it is a quantitative risk assessment method, the scales of severity and probability of occurrence (or likelihood) will be defined quantitatively.



In red : zone whose risk is judged unacceptable
In orange : zone with intermediate risk where a continuous approach of reducing the risk should be sought, with acceptable economic conditions, and given the current state of knowledge and practices and of the vulnerability of the environment surrounding the installation
In green : zone whose risk is judged acceptable

Figure 9 : Risk matrix from French regulation [13]

As we can see on the French regulation's risk matrix above, the scales of severity and probability both have 5 levels. For the severity the levels are defined from "Moderate" to "Disastrous" and for the probability of occurrence the levels are defined from "A" to "E", "A" being the level where the hazard is the most likely to occur and "E" being the level where the hazard is the most unlikely to occur.

4 Benchmarking of Hydrogen Refueling Station risk assessments

4.1 Introduction

The objective of this section is to present the results from the statistical analysis performed. The aim of this statistical analysis is to underline the best practices for the risk assessment of an HRS, and it will be divided into risk assessment and risk acceptance criteria.

The data collected for this analysis were taken from:
- 16 published scientific articles [[14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29]] published from 2008 to 2021 in Japan, Korea, China, Italy and the USA. These articles are actually risk assessments on HRS;
- Answers to a survey from 6 of the consortium members' about their best practices
- 6 safety reviews from the ones published on the h2tools website [30] in 2016 in the USA.

Regarding the selection of published scientific articles, the key words used in the SCOPUS research tool where the following: "risk AND (analysis OR assessment) AND hydrogen AND (refueling OR refuelling OR fueling OR fuelling) AND station)".

Then, the selection was made regarding the publication date (the more recent articles were selected for analysis), the title of the article and the abstract. When these three elements where valid, the article was selected.

The statistical analysis from the data collected is presented bellow and divided into different sub-sections:

- risk assessments methods (4.2),
- risk acceptance criteria (4.3),
- frequency databases (4.4),
- modeling software (**Error! Reference source not found.**,
- critical scenarios (4.6),
- safety barriers (4.7).

Data from published scientific articles in the literature was separated from the data provided by the consortium members and the public industrial reviews. This decision was made because the data from published scientific articles relates to risk assessment studies conducted on specific refueling stations, while the other data relates to methods used generally by consortium member on an unknown number of refueling stations.

4.2 Risk assessment methods

This section presents the results of the statistical analysis conducted regarding risk assessment methods used in HRS. The statistical analysis was conducted in two parts, first the analysis of the data extracted from scientific publications and then the analysis of the data extracted from the consortium members' feedback and from safety reviews.

4.2.1 Statistical analysis' results of the literature

Among the **16 scientific articles studied** from 2008 to 2021 [references [14] to [29]], the risk assessment methods used were identified. Figure 1010 represents the distribution of the methods used.

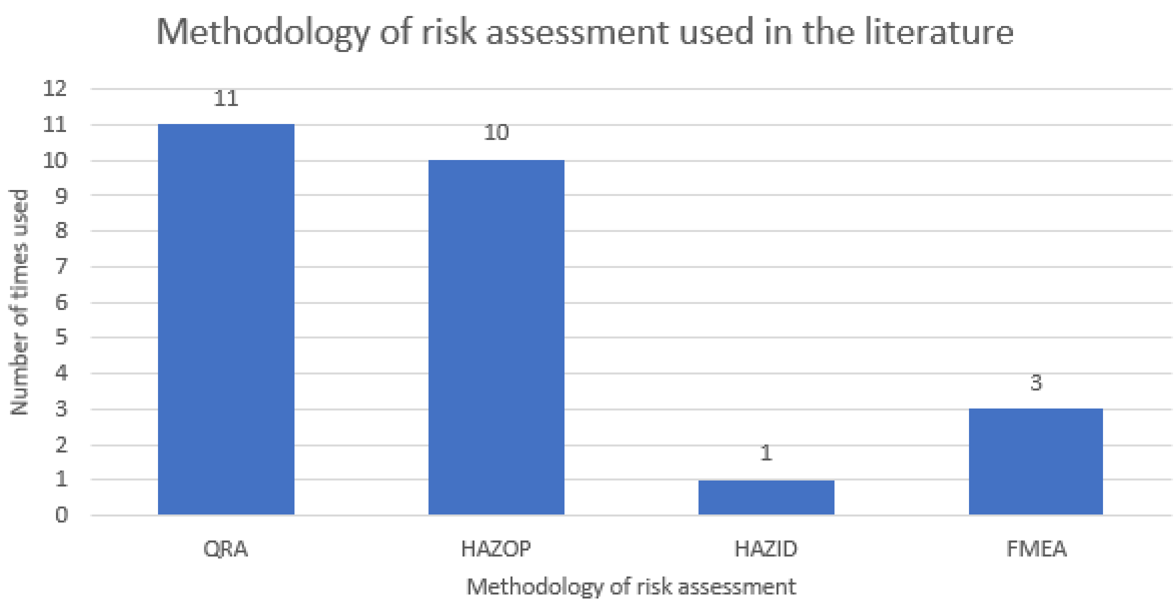


Figure 10 : Distribution of risk assessment methods used for HRS for the 16 articles from the literature

It should be noted that some articles use several risk assessment methods depending on the purpose of the article. As we can see from Figure 1010, the **QRA and HAZOP** methods were predominantly used in the risk assessment of HRS found in the literature.

In addition, Figure 11 highlights which risk analysis methods have been used in each scientific publication according to each country. Among the 16 articles studied in the literature, 5 are from Japan, 5 from China, 2 from Korea, 1 from Italy and 2 from the USA.

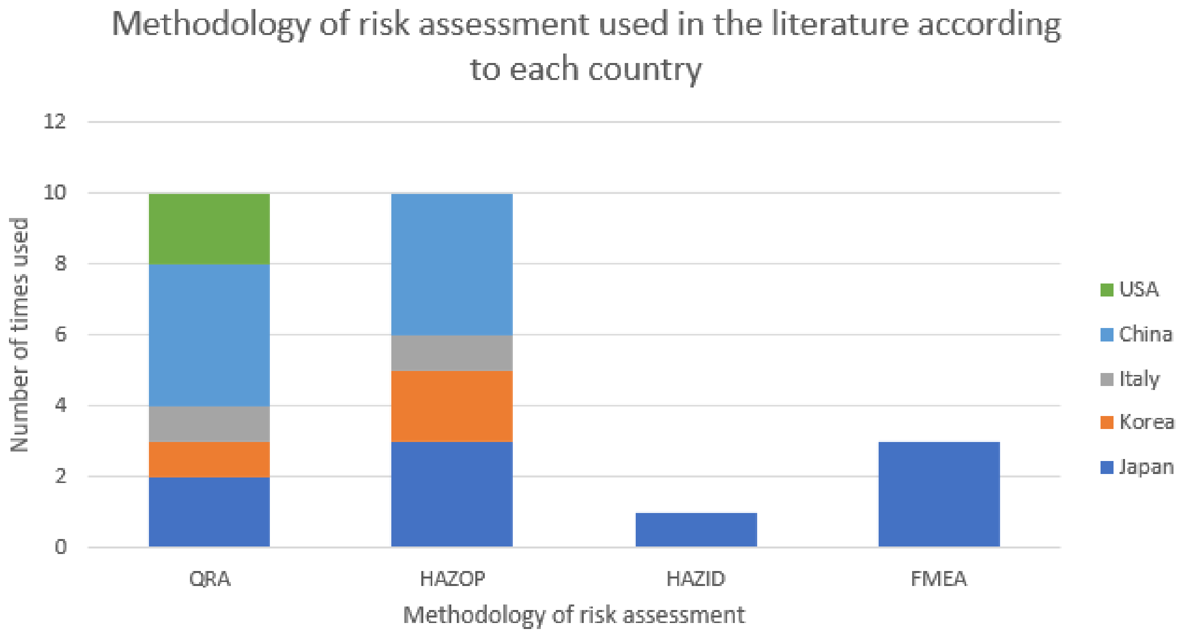


Figure 11 : Distribution of risk assessment methods used for HRS in the literature in Japan, Korea, China, Italy and the USA

It should be noted that some articles use several risk assessment methods. As it can be seen in Figure 11, the Japanese scientific articles use the QRA, HAZID, HAZOP, and FMEA methodologies, which means that there is not one method that is more used than another. On the other hand, in Korea, China and Italy, the risk assessment methods that are most used in the literature are QRA and HAZOP. Finally, in the USA, the only risk analysis method used in the literature is the QRA.

4.2.2 Statistical analysis' results of the consortium members' feedback

Following the collection of data feedbacks from the consortium members and industrials' reviews, we have set up the diagram below. This diagram represents the distribution of the risk analysis methods used by the consortium partners as well as by some industrials (source: H2 tools).

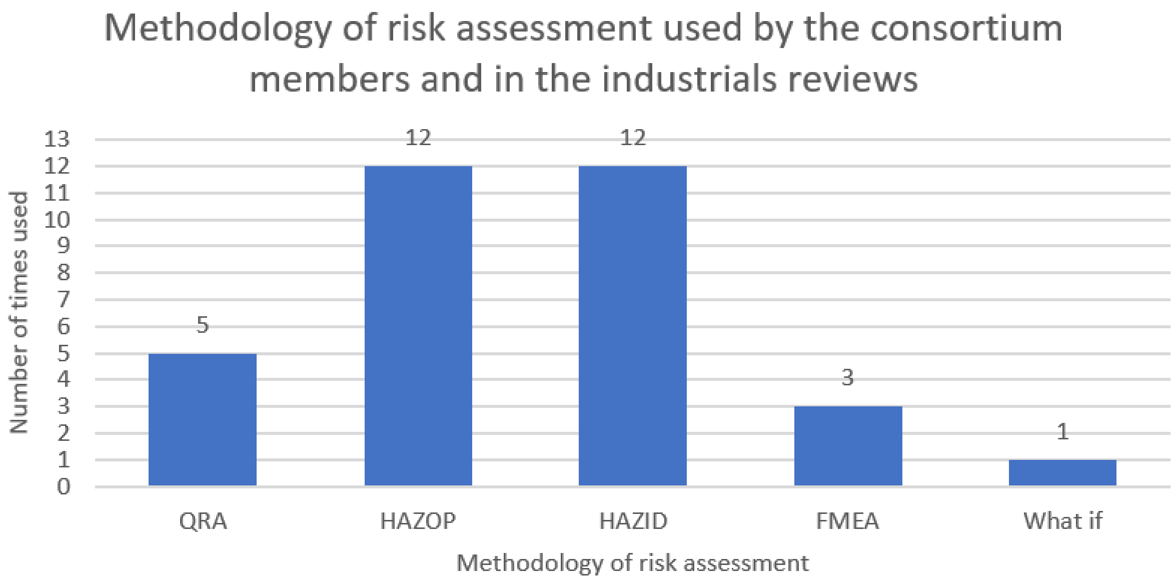


Figure 12 : Distribution of risk assessment methods used by 6 of the consortium members and in the 6 industrial's reviews

It should be noted that some consortium members and industrial reviews use several risk assessment methods depending on the step of the conception of the installation. Even if the architecture is different from a station to another (light and/or heavy vehicle, simple or multi hydrogen dispensers) there is no difference in the methodology used for the risk assessment by the consortium members.

As we can see from Figure 122, the most used risk assessment methods by the consortium members and in the H2 tools safety review are **HAZID and HAZOP**. Usually, an HAZID is performed at preliminary stage of a project and followed by an HAZOP at detailed engineering stage of the project. Moreover, we can observe that the *QRA is used 5 times*, which is not negligible. It can be noticed that QRA is a regulation requirement in some countries (e.g. Netherlands)

4.2.3 Conclusion on the results of statistical analysis for risk assessment methodologies

Regarding the benchmark of the literature and partners best practices, it seems that a quantitative or semi quantitative risk assessment is the most used methodology to apply to an HRS project. Moreover, it is important to note that multiple risk assessment methods can be used for the same installation depending on the step of its conception.
Furthermore, the statistical analysis of the risk assessments in the literature allowed us to see that the methodologies used for the risk assessment are different from one country to another and that some countries have regulation requirements regarding the risk assessment methods to be used (e.g. the Netherlands with the use of QRA)

This finding is aligned with the ISO 19880-1 2020 - Gaseous hydrogen - Fuelling stations - Part 1 : General requirements [2], which recommends that a risk assessment shall be performed for the hydrogen fuelling station except when the stations comply with prescriptive regulations that address relevant risks. It is specified that the risk assessment carried out for the hydrogen fuelling station should be quantitative or semi-quantitative [2].

4.3 Risk acceptance criteria

In this section we present the risk acceptance criteria used in the scientific publications presented in Section 4.1.

Risk acceptance criteria is the parameter which allows the evaluation of risk tolerability. Depending on the risk assessment methodology, the main criteria used are:

- A **risk matrix** where the risk level of an accident is based on the combination of its severity and its probability of occurrence (e.g. used in FMECA).
- A **threshold value** as for example the individual risk which represents the risk of an (unprotected) individual dying as a direct result of an on-site accident involving dangerous substances (e.g. 10^{-6} per year is the value of the risk curve in Netherlands) (e.g. used in QRA)

4.3.1 Risk matrices

During the study of the collected data from scientific publications, partners' feedback and industrials' reviews, very few risk matrices were encountered. Nevertheless, some examples are shown below:

		Frequency			
		1	**2**	**3**	**4**
Consequence severity		**Improbable**	**Remote**	**Occasional**	**Probable**
5	Catastrophic	High (3)	High (3)	High (3)	High (3)
4	Severe loss	Middle (2)	High (3)	High (3)	High (3)
3	Major damage	Middle (2)	Middle (2)	High (3)	High (3)
2	Damage	Low (1)	Low (1)	Middle (2)	High (3)
1	Minor damage	Low (1)	Low (1)	Low (1)	Middle (2)

Figure 13 : Risk matrix n°1 [20]

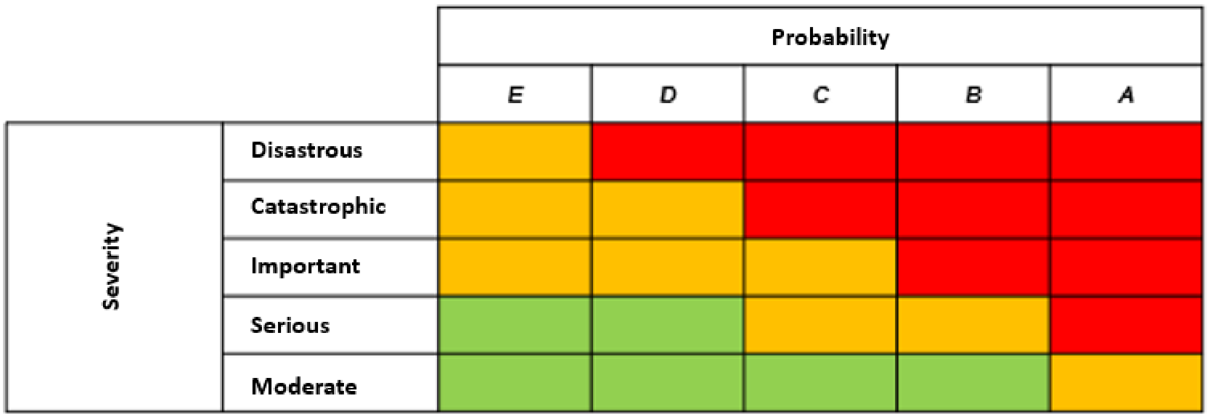
		Probability Level			
Consequence Severity Level		A Improbable	B Remote	C Occasional	D Probable
1	Extremely Severe Damage	H	H	H	H
2	Severe Damage	M	H	H	H
3	Damage	M	M	H	H
4	Limited Damage	L	L	M	H
5	Minor Damage	L	L	L	M

Figure 14 : Risk matrix n°2 [17]

Both matrices give three level of risk : **High (unacceptable) / Medium (Tolerable if As Low as Reasonably Practicable - TifALARP) and Low (acceptable).**

Matrices 1 and 2 (Figure 133 and Figure 144) above are similar: 5 levels of severity and 4 levels of probability. The same four levels of probability have been set from improbable to probable. Five levels of severity were implemented in both matrices. The only difference between the severity levels of the two matrices is in the terms used to describe these levels.

In some countries the use of a risk matrix is required by the regulation (e.g. France), as we can observe in Figure 15. Similar risk matrices are commonly used in the UK as well, with tolerability guidance provided in [31].



In red : zone whose risk is judged unacceptable
In orange : zone with intermediate risk where a continuous approach of reducing the risk should be sought, with acceptable economic conditions, and given the current state of knowledge and practices and of the vulnerability of the environment surrounding the installation
In green : zone whose risk is judged acceptable

Figure 15 : Risk matrix from French regulation [13]

On the other hand, the French matrix (figure 15) has 5 levels for the evaluation of the severity and 5 levels for the probability evaluation. The severity of major accidents is based on the evaluation of the number of people exposed to different levels of intensity of dangerous phenomena. It is noted that the severity is based on the people exposed and does not depend on the number of fatalities. The probability of occurrence ranges from A (higher than 10^{-1} per year) to E (lower than 10^{-5} per year).

		PROBABILITY (per year)				
		A (<0.001)	B (0.01-0.001)	C (0.1-0.01)	D (1-0.1)	E (10-1)
Consequence severity	1 (Catastrophic)	H	H	H	H	H
	2(Severe loss)	M	H	H	H	H
	3 (Major damage)	M	M	H	H	H
	4 (Damage)	L	L	M	M	H
	5 (Minor damage)	L	L	L	L	M

Figure 16 : Rapid Risk Ranking matrix from EIHP project [32]

Moreover, the Rapid Risk Ranking matrix (Figure 16 : Rapid Risk Ranking matrix from EIHP project
) has also 5 levels for the evaluation of the severity and 5 levels for the probability evaluation. As we can see, the five levels of severity were set on a scale from 1 to 5, 1 being the catastrophic level and 5 being the minor damage level. Regarding the five levels for the probability evaluation, they were set up from A to E, A representing a probability of occurrence lower than 10^{-3} and E representing the probability of occurrence going from 1 to 10.

4.3.2 Threshold values

Regarding the threshold value for individual or societal risk, some examples from ISO 19880-1:2020 on Hydrogen refueling stations [2] are listed here, but do not represent an exhaustive list:

- Average Individual Risk: < 10^{-6} deaths per year for vulnerable external populations and 10^{-5} deaths per year for less vulnerable (Dutch source)
- Average Individual Risk: < 2 x 10^{-5}deaths per year for members of the public (Used in NFPA 2 [33] for USA)
- Average Individual Risk: < 10^{-4} deaths per year for facility users and workers [2]

Moreover, this risk acceptance criteria value of 10^{-6} deaths per year is in agreement with the value determined in the European Integrated Hydrogen Project [34] by Norsko Hydro ASA and DNV.

Regarding the Societal Risk, tools for ALARP determination are commonly used in the UK and are presented in a tolerability guidance published by HSE [31]. These tools both calculate the Potential Loss of Life (PLL) also known as Expectation Value (EV) and Risk Integral (RI).
According to HSE's report entitled "Societal Risk : Initial briefing to Societal Risk Technical Advisory Group [35], the PLL or EV is the average number of persons receiving the specified level of harm (i.e. fatality for PLL) per year. The RI is a summary of overall level of societal risk taking into account the whole set of F/N pairs. The following diagram represents the scale of tolerability of the Societal Risk depending on EV and RI.

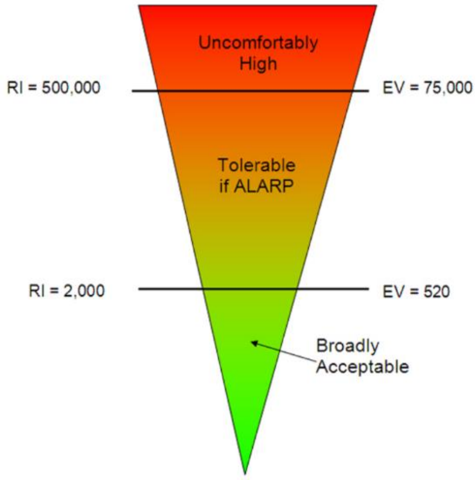


Figure 17 : Scale of the Societal Risk Criteria [31]

As we can see from Figure 17, the boundary value between the “Uncomfortably High” and “Tolerable if ALARP” region is calculated to be a RI of approximately 500 000 or a PLL value of 75 000. The boundary value between the “Tolerable if ALARP” and the “Broadly Acceptable” region is calculated to be a RI of 2 000 or a PLL of 520.

In addition, one important criteria to take into account during the definition of risk acceptance criteria is the possibility of occurrence of domino effects. The domino effects occur when the consequences of an accident lead to an escalation. For example, if the explosion of an equipment (A) generate damage to another equipment (B) which is going to lead to an additional scenario of fire or explosion with consequences worst than the initial scenario on A.

4.3.3 Conclusion on risk acceptance criteria

Regarding the benchmark of the literature and partners best practices, there are two approaches for risk acceptance criteria:
- semi quantitative approach with the use of a matrix
- quantitative approach with the use of Average individual risk or matrix

It is to be noted that some countries have settled the risk acceptance criteria in the regulated framework (e.g. Netherlands or France).

In the case that there is no regulation on the risk acceptance criteria, a discussion with the members of the risk assessment working group is necessary to set up the risk matrix and the threshold value to be used.

4.4 Leak frequencies database

This section presents the results of the statistical analysis conducted regarding leak frequency databases used in the risk assessment of HRS. The statistical analysis was conducted in two parts. First the analysis of the data extracted from scientific publications and then the analysis of the data extracted from the consortium members' feedback and from safety reviews.

In a semi-quantitative approach, the probability of occurrence of each event is assessed qualitatively , but in a quantitative approach the leak frequencies defined in the following section are used. They allow the quantitative evaluation of the probability of an accident. Therefore, the following statistical analysis is only based on the external publications, internal risk analysis, partners' feedbacks and industrials' reviews using quantitative risk assessment methods.

The leak frequencies databases and tools that were used in the sources presented in section 4.1 are the following:

- Sandia National Laboratories
- BEVI/Purple Book
- Japan Nuclear Safety Institute
- Offshore & onshore reliability data
- HID statistics report HSR 2001 002
- Internal data

Sandia National Laboratories [36] is a Federally Funded Research and Development Center operated by the National Technology and Engineering Solutions of Sandia. Moreover, the Sandia National Laboratories is a contractor for the U.S. Department of Energy's National Nuclear Security Administration (NNSA) and supports numerous federal, state, and local government agencies, companies, and organizations. As there was little available data on hydrogen-specific component leakage events that can be used in a QRA, the laboratory establishes data for H2 specific components. Data from different generic sources were collected and combined with few H2 available data using statistical analysis like Bayesian method. First, it allowed the generation of leakage rates for different amounts of leakage. Second, it generated uncertainty distributions for the leakage rates that can be propagated through the QRA models to establish the uncertainty in the risk results. Finally, it provides a means for incorporating limited hydrogen-specific leakage data with leakage frequencies from other sources to establish estimates for leakage rates for hydrogen components.

Purple Book is a part of the Committee for the Prevention of Disasters' guidelines that have been transformed into the Publication Series on Dangerous Substances. It is a report published in 2006 that documents the methods to calculate the risks due to dangerous substances in the Netherlands using the models and data available [10]. The purple book contains frequencies for ignition and loss of containment based on studies related to oil and gas.

The **Reference Manual BEVI Risk Assessment** (or BEVI) [9] is a manual published by the National Institute of Public Health and Environment of the Netherlands in 2009. This manual regroups the information regarding QRA published by the Committee for the Prevention of Disasters in **the Red Book, the Yellow Book, the Green Book and the Purple Book**. Moreover, in this manual all the data regarding frequencies are taken from **the Purple Book**. Therefore, the mention **BEVI/Purple Book** was chosen to refer to these two databases in the following analysis and discussion of this document.

Japan Nuclear Safety Institute was established by the nuclear industry in Japan after the Fukushima Daiichi Nuclear Power Station accident. This organization is primarily focused on nuclear safety and have a clear mission focused on achieving standards of excellence in operations [[37], [38]]. By analyzing NUCIA database which collects incident information of Japanese Nuclear Power plants, JANSI establishes Japanese general equipment reliability data and common cause of failure. The latest version which includes 29years experiences of 56 plants in Japan was opened to the public in June, 2016 [39].

Offshore & Onshore Reliability Data (OREDA) is a project organization composed of oil and gas companies as members. This organization produces comprehensive equipment reliability data to the oil and gas industry and publishes them in handbooks which are updated on a regular basis [40]. It is a data collection program that has been going on since the early eighties. Reliability data has been collected for some 24,000 offshore equipment units comprising approximately 33,000 failures. The project is supported by ten oil companies; AGIP, BP, Elf, Esso, Norsk Hydro, SAGA, Shell, Statoil, and Total. SINTEF has been the main contractor since 1990.
This handbook presents high quality reliability data for offshore equipment collected during phase VI to IX (project period 2000 – 2009) of the OREDA project. The intention of the handbook is to provide both quantitative and qualitative information as a basis for Performance Forecasting or RAMS (Reliability, Availability, Maintainability and Safety) analyses

Offshore Hydrocarbon Release Statistics 2001 HID statistics report HSR 2001 002 is a report published in 2001 by Health & Safety Executive (UK), [41]. The purpose of this report is to provide the offshore industry with data from the HydroCarbon Releases (HCR) Database for their use in connection with the preparation and revision of offshore safety cases, particularly in Quantified Risk Assessment (QRA). It covers the period 1992 to 2001 with around 2000 hydrocarbon releases in the UK offshore sector.

4.4.1 Statistical analysis' results of the literature

Twelve of the sixteen **scientific articles studied** from 2008 to 2021 are using leak frequency databases in order to assess the risks quantitatively. The following diagram represents the distribution of databases used in these articles.

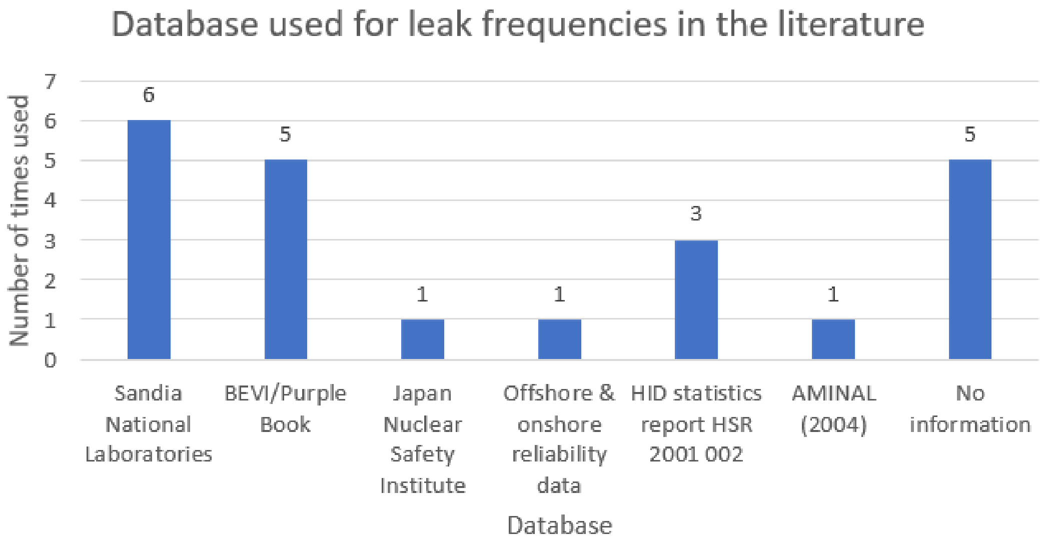


Figure 18 : Distribution of databases of leak frequencies used for HRS for the 16 articles identified in the literature

It should be noted that some articles use several databases. As seen in Figure 18, the most used databases are **BEVI/Purple Book and Sandia national Laboratories' database**.

4.4.2 Statistical analysis' results of the consortium members' feedback

Following the collection of data from the consortium members and industrials' reviews, we have set up the diagram below. This diagram represents the distribution of the databases of leak frequencies used by consortium members but does not take into account the industrial reviews since there were no information of a database used for leak frequencies in h2tools website [30].

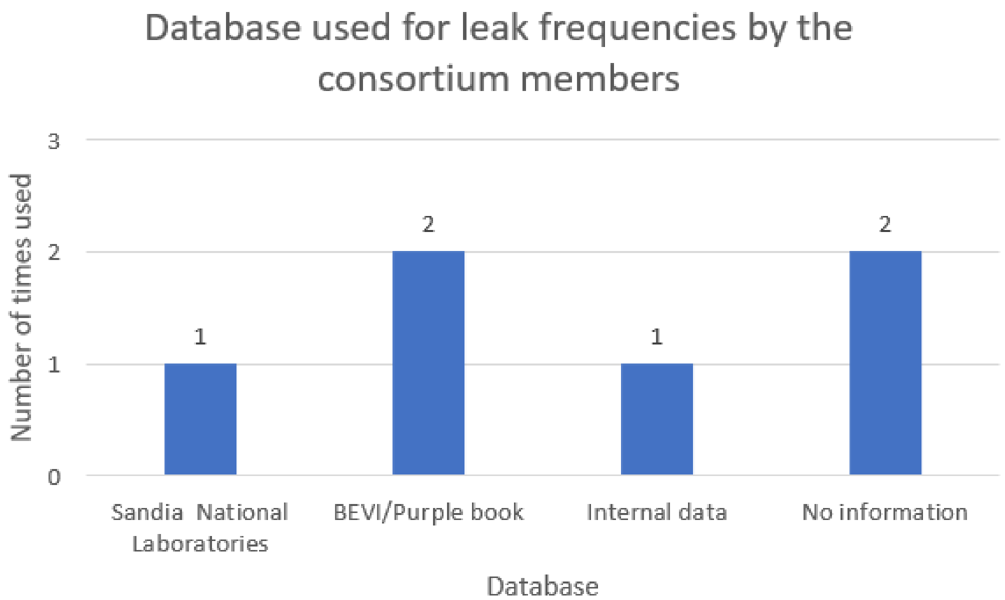


Figure 19 : Distribution of databases for leak frequencies used by 6 of the consortium members

As we can see in Figure 19, most of the consortium members use **BEVI/Purple Book** as a database for leak frequencies. Unfortunately, a large part of the collection of data studied does not give information about the database used for leak frequencies.

4.4.3 ISO 19880-1 2020 - Gaseous hydrogen — Fueling stations Part 1 General requirements

Regarding databases for frequencies, this standard ISO 19880 uses, in its annex A, Sandia Laboratories database (through Hyram software) and historical data from the UK Health and Safety Executive, Hydrocarbon Release Database since 1992 from operators of the North Sea (through SAFETI software) for QRA.

4.4.4 Conclusion on the results of the statistical analysis of leak frequencies database

The most used databases for leak frequencies in a HRS are **BEVI/Purple Book** (not specific to H_2) and **Sandia National Laboratories' database** (specific to H_2). Companies with sufficient internal return of experience specific on H2 could use or complete the previous data with their **internal database**. During task 3.4 (detailed risk assessment of the critical scenarios identified in task 3.3) a specific review of the data available for the likelihood evaluation will be achieved. It will allow to confirm the relevancy of these databases compared to what is needed and to identify potential missing data for likelihood evaluation of the critical scenarios identified in task 3.3.

4.5 Modeling tools/software

4.5.1 Introduction and modeling tools presentation

This section presents the results of the statistical analysis conducted regarding modeling tools and software used in the risk assessments of HRS. The statistical analysis was conducted in two parts. First the analysis of the data extracted from scientific publications and then the analysis of the data extracted from the consortium members' feedback and from safety reviews.

4.5.1.1 Integral type modeling tools

According to [2], a brief description of the software/tools currently used for the evaluation of the consequences for H_2 accidents is presented below :

HyRAM [42] : a toolkit that integrates deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing hydrogen hazards' impact on people and structures. HyRAM incorporates generic probabilities for equipment failures and probabilistic models for heat-flux impact on humans and structures, with computationally and experimentally validated models of hydrogen release and flame physics.

Phast/Phast Risk: A process hazard analysis software tool, available from DNV GL, for all stages of design and operation, which examines the progress of a potential incident from the initial release to

far-field dispersion analysis including modelling of pool spreading and evaporation, and flammable and toxic effects.
Moreover, PHAST is also used in combination with DNV GL's proprietary Unified Dispersion Model. Actually this combination allowed the creation of a software tool named **SAFETI-NL** used for quantitative risk assessment calculations in the Netherlands. It has been developed by Det Norske Veritas GL (DNV GL) [43] and it is used to carry out quantitative risk analysis of onshore process, chemical and petrochemical facilities or analysis of chemical transport risk.

Moreover, some companies have developed their own software/models (i.e **ALDEA** for Air Liquide or **FRED** for Shell or EFFEX, PROJEX and EXOJET assembled in the EPHEDRA tools platform for INERIS).

4.5.1.2 CFD tools

FLACS [44]**:** A suite of 3D computational fluid dynamic tools with a series of standard modules and additional bolt-ons designed to meet specific requirements. This software is used for ventilation, gas dispersion and explosion simulations in safety analyses,
including a fire module.

KFX-Exsim: A CFD tool developed by DNV GL [45]. It is a 3D explosion simulation software technology used on offshore and onshore facilities. It allows the optimization of layout to reduce explosion consequences and the quantification of blast wave load acting on safety critical objects such as temporary refuge, lifeboats and living quarters. Moreover, this software gives a probabilistic explosion analysis, a ALARP and cost-benefit analysis of mitigating measures and is used for accident investigations.

4.5.2 Statistical analysis' results from the literature

Among the scientific publications studied from **2008 to 2021**, we collected data regarding the software used for the risk assessment. The following diagram represents the distribution of the use of software in the **16 scientific publications** studied.

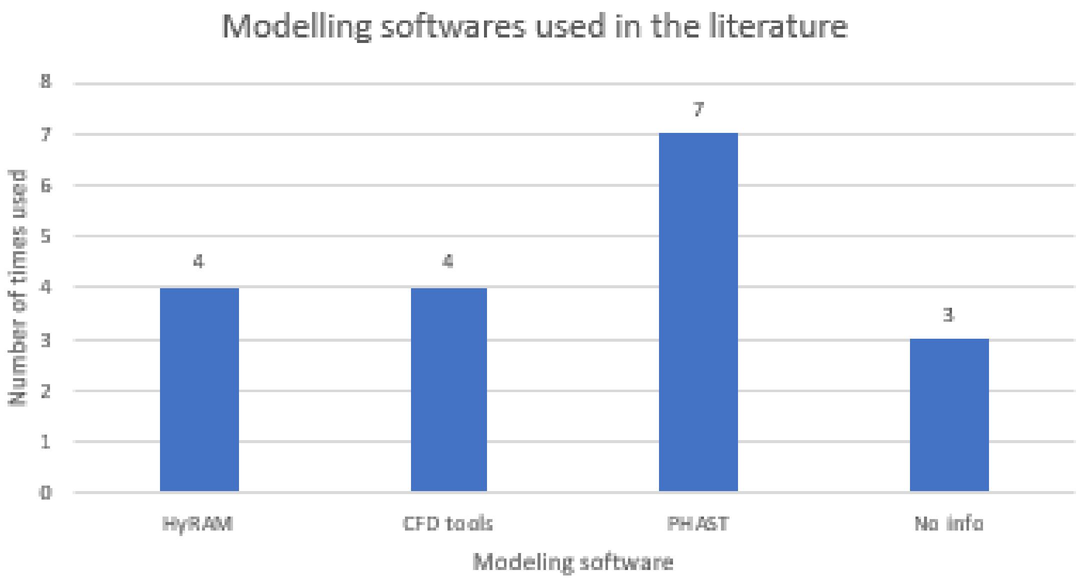


Figure 20 : Distribution of the modeling software used for HRS for the 16 articles identified in the literature

It should be noted that some articles use several modelling software. As it can be seen from Figure 20, the most used software is PHAST. However it is important to mention that CFD tools and HyRAM are also commonly used.

4.5.3 Statistical analysis' results of consortium members' feedback

Following the collection of data from internal risk assessments, feedback from our partners and industrials' reviews, we have set up the diagram below. This diagram represents the distribution of the modeling software used by the project partners.

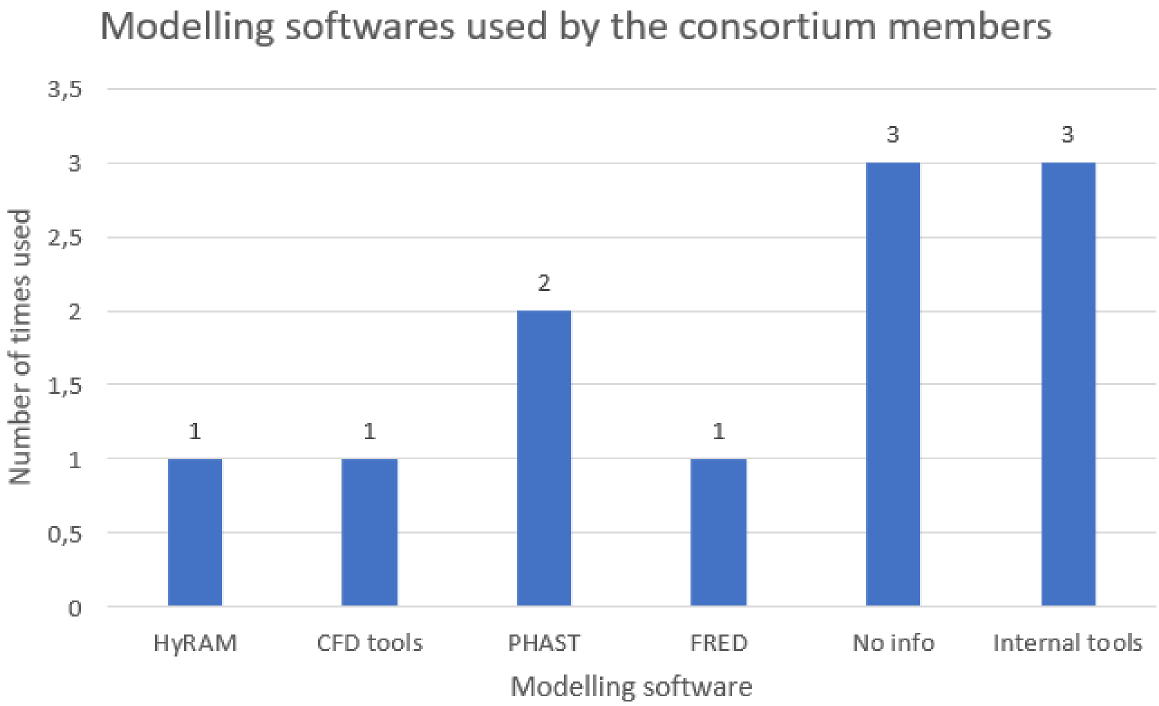


Figure 21 : Distribution of the modeling software used by 6 of the consortium members

As we can see in Figure 21 the most used modeling software are internal tools and PHAST. Moreover, even though it is less used, we note that HyRAM, FRED and CFD tools are used in a few cases.

4.5.4 Conclusion on the results of statistical analysis of modeling tools

The modelling tools currently used are the **PHAST** (not specific to H_2), **Hyram** (specific to H_2) and **internal tools** (e.g. : Aldea, EFFEX). CFD tools could be used for specific scenario or configuration (e.g. confined explosion).

4.6 Safety critical scenarios

This section presents the results of the statistical analysis conducted regarding the safety critical scenarios that were the mostly used in the risk assessment of HRS.

Regarding the safety critical scenarios (SCEs), a list has been established below. This list represents the critical scenarios that have been studied in the scientific literature (16 articles from 2008 to 2021).

Alternative methods of distilling SCEs exist, for example use of risk matrices to determine where the events sit in the matrix, allowing the ranking of risks. Safety critical events are defined as those events which dominate the contribution to the overall risk. Where a semi-quantitative approach has been used, the determination of safety critical events can simply be achieved by considering those events with the highest frequency in each severity band.
Exceptions to this are taken to include those where an event has a lesser frequency than an event in a greater severity band, and any injury that has a frequency less than 2 orders of magnitude greater than the greatest fatality. In addition, any scenario that can result in more than 50 fatalities is chosen.

This approach, however, is only valid if the other scenarios are reviewed for any unusual or high consequence events at lower frequency which could make a significant contribution to the risk and for low risk events which could escalate to a more serious event (e.g. unlikely events with safeguard reliance on human intervention). The main critical scenarios found from the literature review through this task (not risk matrices approach) are related to two accidental events:

- Catastrophic ruptures (including burst of capacity)
- Hydrogen leakage

More detailed work on the establishment of the SCEs will be conducted as part of Task 3.5

The equipment concerned by the catastrophic ruptures is the following:

- Tube trailer
- Compressor
- Dispenser
- Flexible hose
- Hydrogen storage
- Pipework

Theses ruptures can also occur, for example, due to external events such as automobile collision, building collapse, helicopter crash [21] or natural disasters like seismic activity [16].

The equipment concerned by the hydrogen leakage is the following:

- Compressor
- Cylinder of hydrogen storage
- Dispenser

- External piping
- High Pressure accumulator
- Buffer storage
- Tube trailer

It is important to note that leaks from vehicle fittings can also occur as mentioned in [15]. The above list can be used as a help for the risk assessments of HRS, however it is not an exhaustive list.

The leak of hydrogen can be very dangerous. In fact, it can lead to phenomena such as jet fire, flash fire, deflagration or detonation.

The following dangerous phenomena will lead to **thermal effects**:

- **Jet fires** occur when the leaking hydrogen is immediately ignited and creates a continuous flame in the direction of the leakage leading to radiative effects;
- **Flash fires** occur when the ignition of the leaking hydrogen is not instantaneous. The hydrogen disperses and is mixed with the surrounding air for a duration to create a flammable cloud and then meets an ignition source. Furthermore, the flash fire happens over a very short duration.

The following dangerous phenomena will lead to **overpressure effects**:

- Vapour Cloud Explosion (**VCE**) when the leaking hydrogen lead to an explosive atmosphere in a confined space (e.g. electrolyzer or compressor container) with delayed ignition;
- Unconfined Vapour Cloud Explosion (**UVCE**) when the leaking hydrogen lead to an explosive atmosphere in a unconfined space (e.g. outside H2 piping leakage with obstacles around) with delayed ignition.

Depending on various parameters (e.g. congestion, energy of the ignition source,…) we observe two types of **explosion**:

- Deflagrations occur when the flammable cloud of hydrogen/air is ignited and produces a subsonic shockwave.
- Detonations occur the flammable cloud of hydrogen/air is ignited and produces supersonic shockwave it produces thanks to the acceleration of the flame front

4.6.1 Statistical analysis' results of literature

Regarding the scenarios of higher risk, a statistical study has been conducted using the 16 articles of the scientific literature.
We collected the data regarding equipment of the HRS that are considered in scenarios of higher risk. It should be noted that each equipment was considered with its pipes, fittings and valves. The following diagram represents the number of times each equipment was mentioned in the literature.

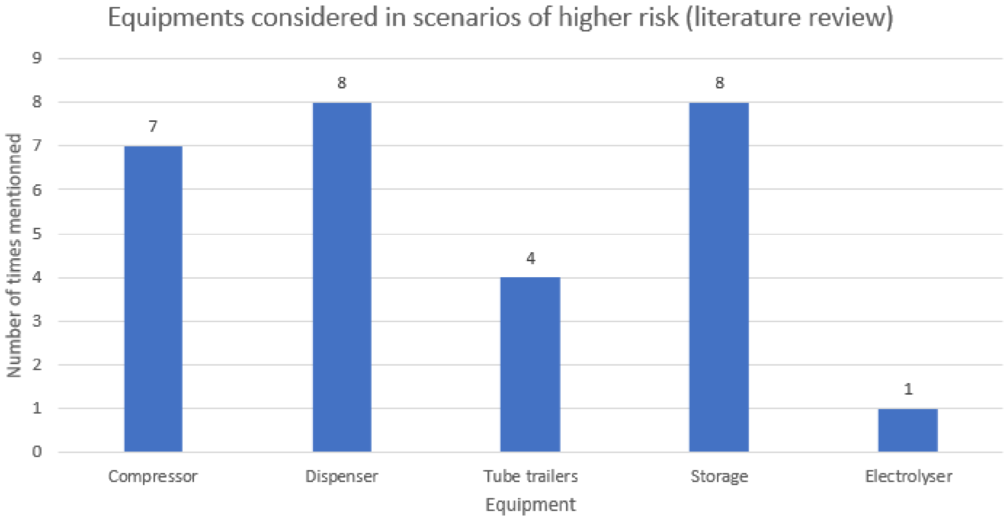


Figure 22 : Distribution of the equipment considered in scenarios of higher risk for HRS for the 16 articles identified in the literature.

As we can see in Figure 22 the equipment with the higher risk of HRS are **dispensers, storages, compressors**. Thus, we focus our statistical analysis on these 3 pieces of equipment by collecting data regarding the scenarios of higher risk and safety barriers linked to each equipment. Moreover, the statistical analysis on safety barriers regarding this equipment is presented in the paragraph 4.6.

In addition, according to the **lessons learned from the analysis of accidents involving HRS in Japan from 2005 to 2014 and in USA from 2004 to 2012** [46], the following list of equipment concerned by scenarios of higher risk was established:

- Compressor (including joints)
- Pipework
- Pressure relief valve
- Dispenser
- Screw joint
- Flange joint
- Valves
- Fuel Cell Vehicle’s filling port
- Electrolyzer
- Storage (accumulators)
- Adapter

Moreover, in order to have an idea of the number of times each equipment was mentioned, we plot the following diagram:

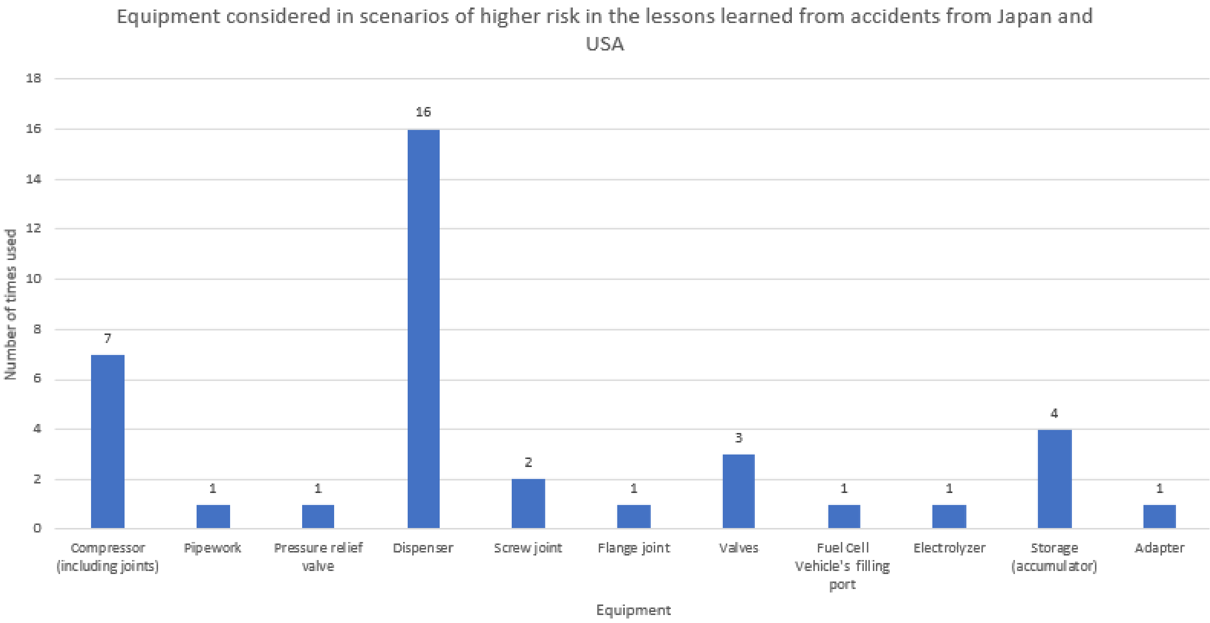


Figure 23 : Distribution of the equipment considered in the lessons learned from accident involving HRS in Japan and the USA.

As we can see from Figure 23, the lessons learned from the accidents involving HRS in Japan and USA confirm our literature review: **dispensers, compressors and storages** are the equipment that are the mostly concerned by accidents.

The following diagram represents the distribution of the scenarios of higher risk that were mentioned regarding the **compressors** of HRS in the literature.

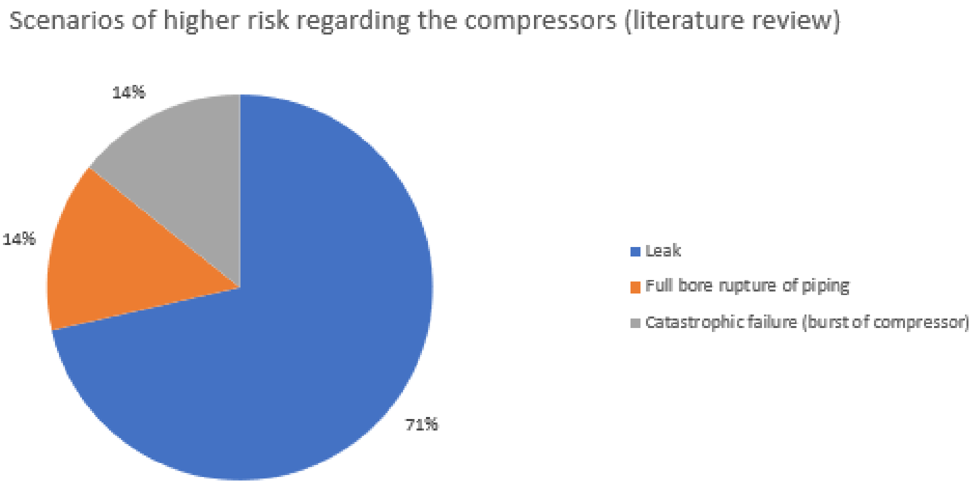


Figure 24 : Distribution of the scenarios of higher risk regarding the compressors of HRS mentioned in the literature.

As we can see on the diagram above, the scenario of higher risk regarding compressors in a HRS that is the most commonly mentioned in the literature is a leak on the compressor (e.g. leak on filter, leak from connection piping). The higher risk ranking can be explained by the high frequency of small leaks on compressor accessories compared to a full bore rupture or catastrophic failure.

The following diagram represents the distribution of the scenarios of higher risk that was mentioned regarding the **dispensers** of HRS in the literature.

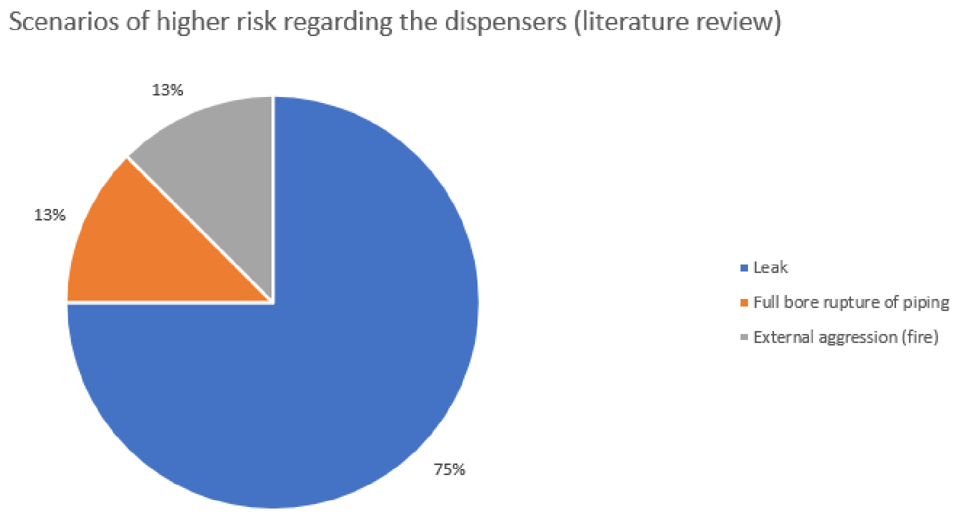


Figure 25 : Distribution of the scenarios of higher risk regarding the dispensers of HRS mentioned in the literature.

As we can see on the above diagram (Figure 25), the scenario of higher risk regarding **dispensers** in a HRS that is the most commonly mentioned in the literature are the **leaks** (e.g. leak on hose, leak on filter, leak in dispenser). It can be explained by the number of accessories /instrumentation/connection in this system which can lead to various small leaks.

The following diagram represents the distribution of the scenarios of higher risk that was mentioned regarding the **storage** in a HRS in the literature.

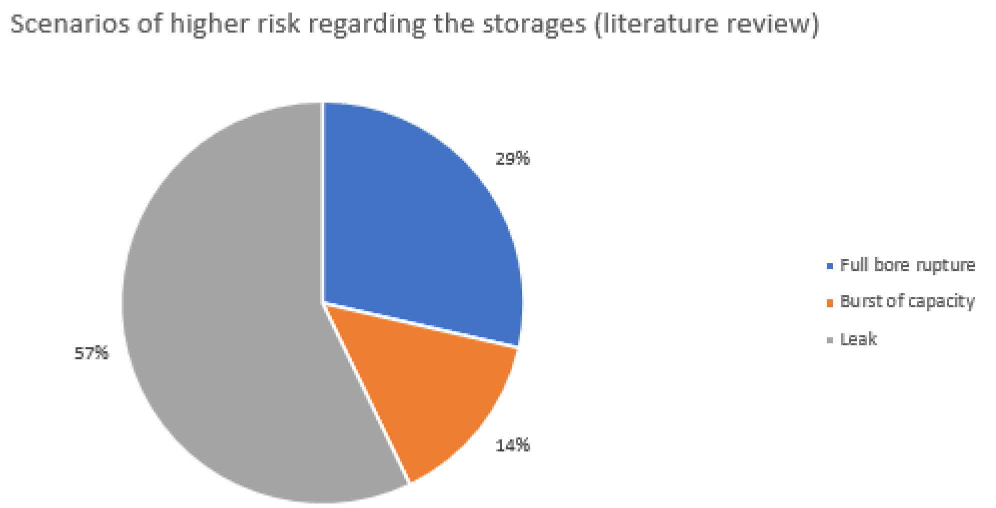


Figure 26 : Distribution of the scenarios of higher risk regarding the storage in a HRS mentioned in the literature.

As we can see on the above diagram (Figure 26), the scenario of higher risk regarding storage in a HRS that is the most commonly mentioned in the literature is the **leak from hydrogen storage** (e.g.

leak from a tank). The higher risk ranking can be explained by the high frequency of small leakage on the storage accessories compared to a full bore rupture, a leak on valves, a rupture of instrument piping or a catastrophic failure.

In addition, in the **analysis of lessons learned from accidents involving HRS in Japan and the USA** [46], the classification of incidents and accidents that occurred was made following these 6 categories:

- leakage due to the damage and fracture of main bodies of apparatuses and pipes (including welded parts) (***Leakage 1***)
- leakage from flanges, valves, and seals (including deteriorated nonmetallic seals) **(*Leakage 2*)**
- leakage due to other factors, e.g., human error and external impact (***Leakage 3***)
- Explosion and fire
- Burst and fracture
- Others

Moreover, in order to have an idea of the distribution of the scenarios, we plot the following diagram:

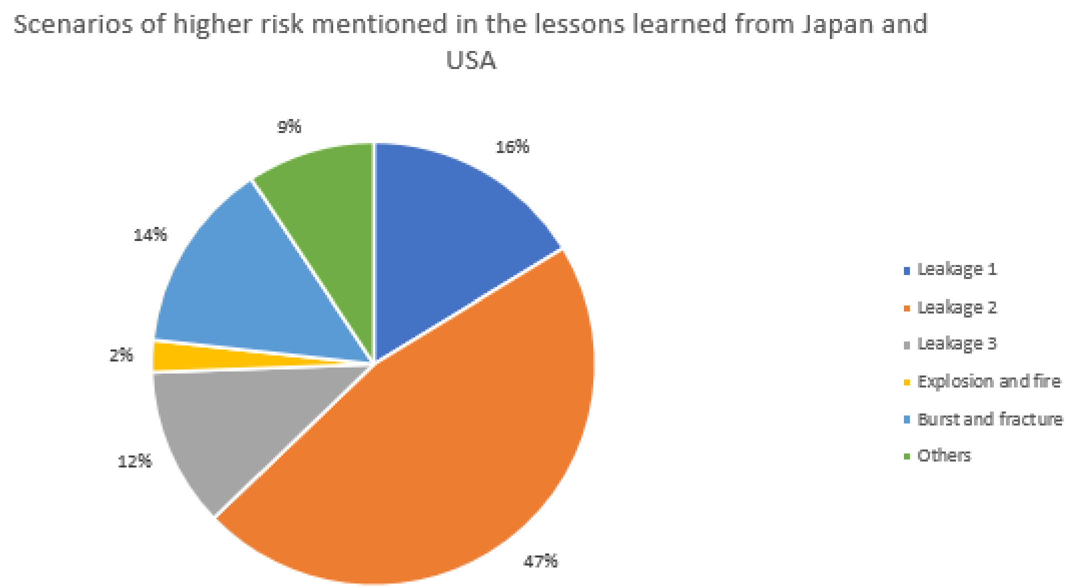


Figure 27 : Distribution of the scenarios mentioned in the lessons learned from accidents involving HRS in Japan and the USA

As we can see on the above diagram, the most frequent scenarios that occurred according to the lessons learned from accident involving HRS in Japan and the USA are:

- **leakage from flanges, valves, and seals** (including deteriorated nonmetallic seals);
- **leakage due to damage and fracture of main bodies of apparatuses and pipes** (including welded parts).

Furthermore, in order to confirm our literature review and analysis on the equipment, Figure 28 shows the number of times each equipment was concerned by the leakages 1 or 2 in the lessons learned from accidents involving HRS in Japan and USA.

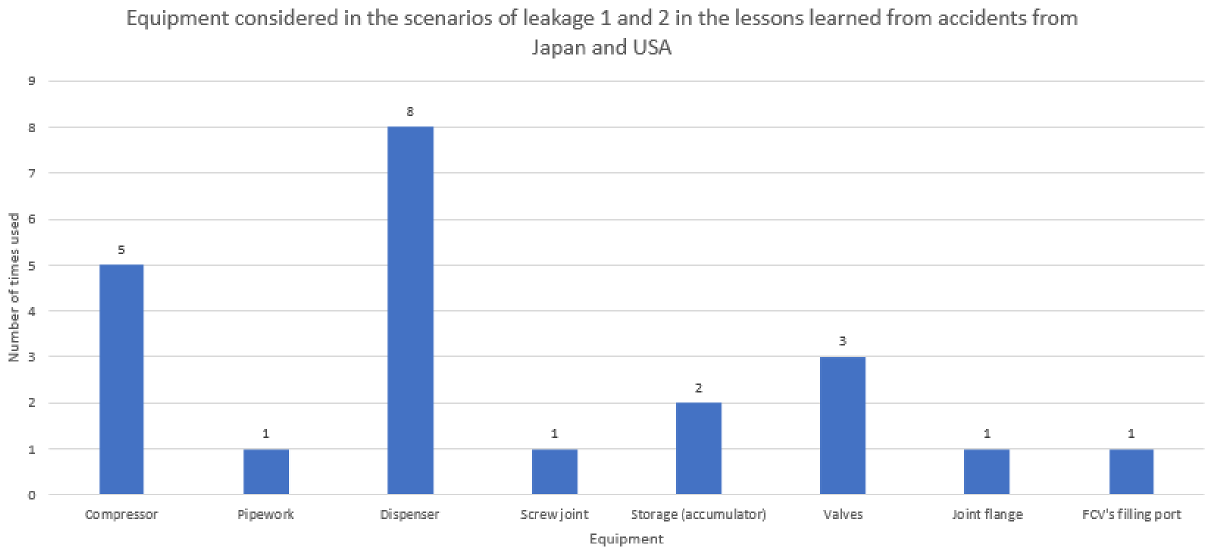


Figure 28 : Distribution of the equipment considered in the scenarios of leakage 1 and 2 in the lessons learned from accidents from Japan and USA

As we can see in Figure 28, the equipment that has been most concerned by the scenarios of leakage 1 and 2 in the lessons learned from accidents from Japan and the USA are the **dispenser and the compressor**.

4.6.2 Conclusion on the results of statistical analysis of HRS safety critical scenarios

The compressor and the dispenser including their accessories are the equipment that are the mostly concerned by accidents in general and classified of higher risk according to literature review. Moreover, we observed that **the storages** are also very sensible equipment.

According to lessons learned, the most frequent scenarios on these equipment are the following:

- **leakage from flanges, valves, and seals**;
- **leakage due to damage and fracture of main bodies of apparatuses and pipes.**

4.7 Safety barriers

4.7.1 Introduction

Regarding the safety barriers to be set up in a HRS, the following table represents the safety barriers mentioned in the scientific literature and they are classified according to INERIS classification [47]:

Table 13 - Non exhaustive list of safety barriers for HRS.

Name	Active safety barrier	Passive safety barrier	Safety Instrumented Function
Shutoff valve including in a SIF automatic sequence			X
Emergency Shutdown System ord Device (e.g. push button leading to a safe automatic actions to shutdown the hydrogen system)			X
Pressure monitoring on piping/storage to detect a leak associated to safe automatic actions to shutdown the hydrogen system			X
Pressure switch (e.g. PSHH leading to an automatic emergency venting)			X
Flame detection associated to safe automatic actions to shutdown the hydrogen system			X
Hydrogen detectors or sensors associated to safe automatic actions to shutdown the hydrogen system			X
Breakaway couplings for the flexible hoses	X		
Excess flow valves	X		
Relief valves	X		
Rupture discs		X	
Fire protection walls		X	
Blast walls		X	
Explosion vent (e.g. container)		X	
Separation distances		X	
Segregation of hazardous materials		X	

Although Table 13 can provide suggestions for the risk management of HRS and some of the points may be used in combination with one another to ensure redundancy, it should be noted that it is not an exhaustive list.

The exhaustivity of the safety barriers will be confirmed by task 3.3, related to preliminary risk assessment. The detailed risk assessments (tasks 3.4/3.6) will require specific data on some of these safety barriers related to critical scenarios. For these specific barriers, the ability to study their effectiveness, response time and probability of correct operation (or probability of failure) is required. The overall evaluation of their performances (in particular response time and effectiveness) could be achieved using some databases with data related to frequencies of safety barriers failure.

4.7.2 Statistical analysis' results of literature

To have a first overview of important safety barriers related to HRS, a statistical study has been conducted based on literature review. In this study we focused on the safety barriers related to the equipment considered in scenarios of higher risk identified in Section 4.6.

The following analysis is only an overview of the highlighted safety barriers and shall not be considered as recommendations. The final recommendations for HRS safety barriers will be released during task 3.7 best practice guidelines redaction.

The following diagram represents the distribution of the safety barriers regarding the scenarios on compressors for HRS in the literature.

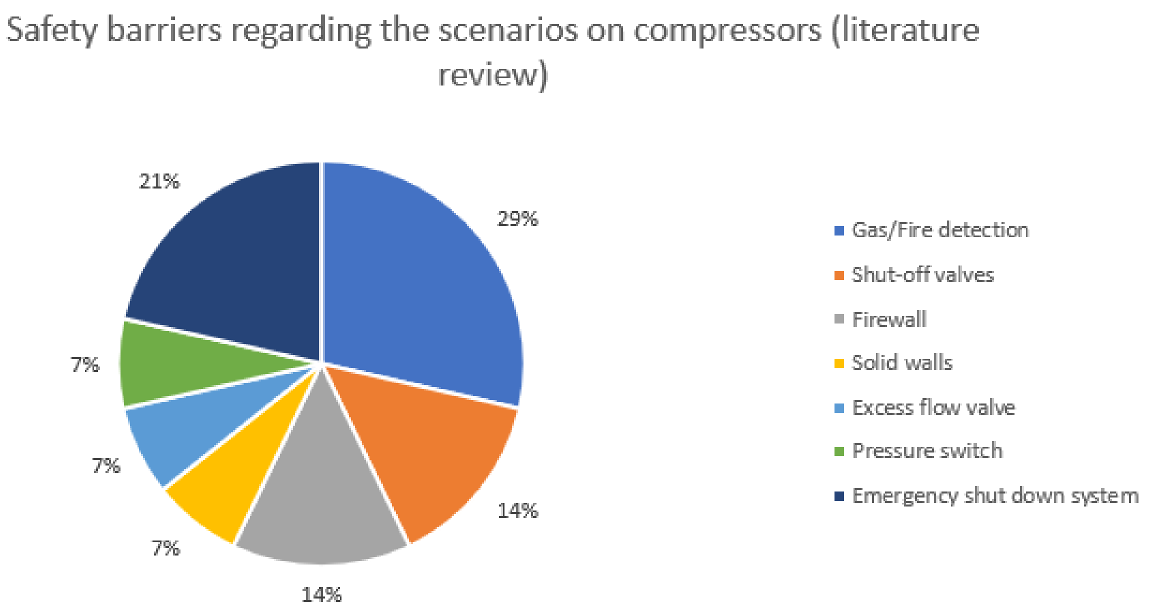


Figure 29 : Distribution of the safety barriers regarding the compressors' scenarios of HRS mentioned in the literature.

As we can see in the above diagram, the safety barriers regarding the **scenarios of higher risk** on **compressors** (leaks) in an HRS that are the most commonly mentioned in the literature are the **gas and fire detectors and the emergency shutdown system related** (the sensors will detect the leak or fire and will generate an automatic emergency shutdown procedure of the system). Furthermore, it is mentioned that shut-off valves (included in a SIF) and firewalls are also frequently employed as efficient safety barriers for hydrogen compressors.

The following diagram represents the distribution of the safety barriers regarding the scenarios on dispensers of HRS in the literature.

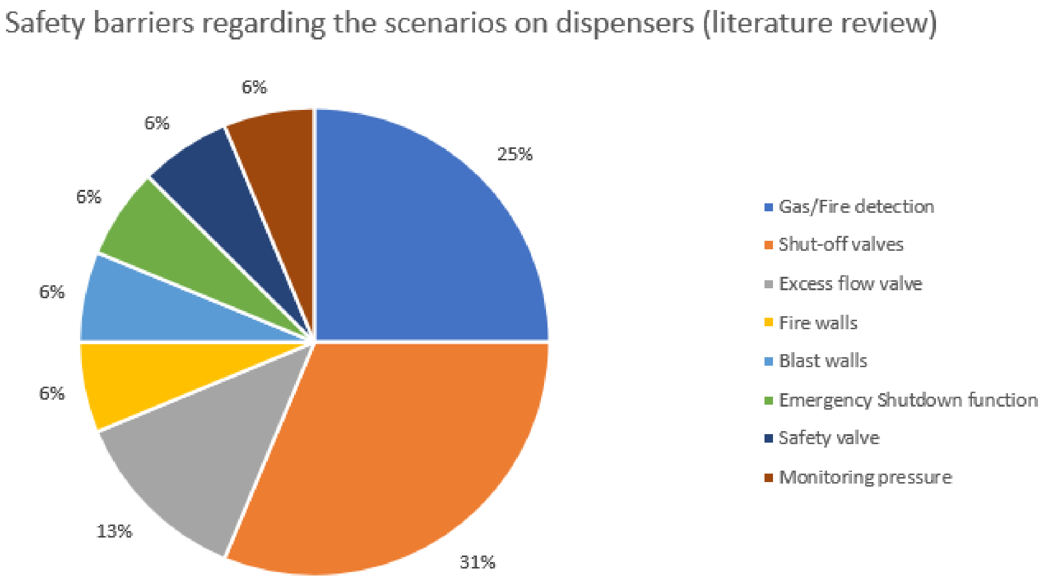


Figure 30 : Distribution of the safety barriers regarding the dispensers' scenarios of HRS mentioned in the literature.

As we can see in Figure 30, the safety barriers regarding the **scenarios of higher risk on dispensers** (leaks) **in a HRS** that are the most commonly mentioned in the literature are the **gas and fire detectors** with the automatic safe shutdown related **and the shut-off valves** as part of an SIF.

The following diagram represents the distribution of the safety barriers regarding the scenarios on storages of HRS in the literature.

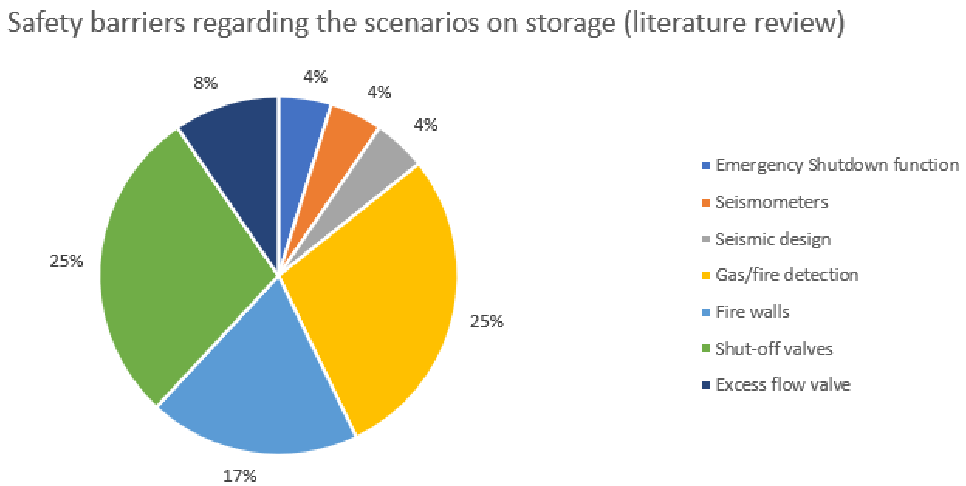


Figure 31 : Distribution of the safety barriers regarding the scenarios on storages of HRS mentioned in the literature.

As we can see in Figure 31, the safety barriers regarding the higher risks scenarios on **H_2 storages** (leaks on storage, on piping or on valve) in an HRS that are the most commonly mentioned in the literature are **firewalls, gas and fire detectors** with the automatic safe shutdown related **and shut-off valves** as part of an SIF.

4.7.3 Conclusion on the results of the statistical analysis of HRS safety barriers:

The highlighted safety barriers mentioned for the safety critical scenarios identified are:
- **gas and fire detectors** with the automatic safe shutdown related;
- **shut-off valves** as part of an SIF;
- **Emergency Shutdown Device** (associated to a SIF);
- **firewalls.**

4.8 Conclusion for the state of the art of risk assessment on HRS

Since the installation of HRS for the public is new in the industrial field, there is not yet much data and information regarding the risks associated with such a facility in the literature. Thus, the risk assessment related to these stations may differ in terms of the methods used, the assumptions made, the tools used and the sources of information needed for the risk analysis.

Nevertheless, thanks to the bibliographic research in the scientific literature as well as the gathering of information from the project partners and industry survey, we have succeeded in setting up a statistical analysis allowing us to report on the current general practices concerning HRS risk assessment. Thus, regarding the most used risk assessment methods, we observe that a fully quantitative or semi quantitative risk assessment is the most commonly used method to apply to an HRS project.

HAZID is useful at preliminary stage of HRS project for lay out and compatibility of HRS with its environment.
It is often completed by a **HAZOP** study during detailed engineering phase in order to study the risks related to equipment and process.
These risk assessments will allow us to identify, using qualitative ranking tools, the potential safety critical scenarios to be studied in detail. The detailed study is a quantification of the risk through likelihood and severity evaluation. This quantification is generally focused on the scenarios with the highest consequence distances. Thanks to this quantification step, the risks related to the implementation of an HRS can be evaluated.

In various countries a full QRA is required by regulation for HRS, which makes it necessary to be mindful of potential domino and escalation effects which affect the HRS as well as the populations surrounding it. Indeed, the combination of methods among these enables us to conduct an adequate risk assessment by taking into account the risks related to the installation and its environment as well as the risks related to the process within an HRS.

Furthermore, the statistical analysis allowed us to highlight databases mentioned in articles and used by partner for leak frequencies related to HRS risk assessment. It was found that the data from **BEVI/Purple Book** (non-specific to H2) **and Sandia National Laboratories** (adapted to H2) are the most commonly used.
Quantitative risk assessment requires the modeling of hazardous events. Thus, the statistical analysis revealed that the most used modeling software for the risk analysis of an HRS are **PHAST**

(non-specific to H_2)**, CFD tools** and **HyRAM / internal tools** (adapted to H2)**.** Nevertheless, it is important to highlight that modeling software such as, Safeti are sometimes used to carry out QRA.

Finally, the literature review and lessons learned was very useful in order to establish a non-exhaustive lists of critical scenarios:

- leakage from flanges, valves, and seals on **compressor** / **dispenser / storage**
- leakage due to damage and fracture of main bodies of apparatuses and pipes from **compressor / dispenser / storage**)

The main safety barriers identified for these scenarios are:

- **fire and gas detection** to detect a leak and safely shutdown the H2 system with an **ESD**
- **shutoff valve** as part of a SIF to reduce/avoid the loss of containment
- **fire walls** to avoid escalation/dominos effect (protection barrier).

These lists could be useful during the development of Tasks 3.3 and 3.4 of the Multhyfuel project (preliminary and detailed risk assessment).

5 Benchmarking of conventional refueling station risk assessments

5.1 Introduction

The objective of this section is to present the results of the statistical analysis performed on conventional refueling stations (Gasoline, LNG, LPG, CNG and electrical charging stations). The data collected for this analysis were taken from:

- 8 published scientific articles [[48] [49] [50] [51] [52] [53] [54] [55]]
- Answers from the consortium members to survey regarding their practices on risk assessment of conventional refueling stations.
- 2 safety reviews or reports published by external organizations [[56] [57]]

Regarding the selection of published scientific articles, the key words used in the SCOPUS research tool where the following:
"risk AND (assessment OR analysis OR evaluation) AND (petrol OR gas OR cng OR lpg OR gasoline OR diesel OR electrical) AND (fuel OR fueling OR fuelling OR refueling OR refuelling) AND station"
Then, the selection was made regarding the publication date (the more recent articles were selected for analysis), the title of the article and the abstract. When these three elements where valid, the article was selected.

The statistical analysis from the data collected is presented bellow and divided into different sub-sections:

- risk assessments methods (5.2),
- risk acceptance criteria (5.3),
- frequency databases (5.4),
- modelling software (5.5),
- safety critical scenarios (5.6),
- safety barriers (5.7).

For this analysis, data from published scientific articles in the literature were separated from the data provided by the consortium members and the external organizations' reviews and reports. We justify this decision by the fact that the data from published scientific articles are related to studies conducted on specific refueling stations, whereas the data from partners are related to methods used generally by that particular consortium member and external organizations without scrutiny and knowledge about the number of refueling stations taken into consideration.

5.2 Risk assessment methods

This section presents the results of the statistical analysis conducted regarding risk assessment methods used in conventional refueling stations. The statistical analysis was conducted in two parts. First the analysis of the data extracted from scientific publications and then the analysis of the data extracted from the consortium members' feedback and from the external organizations' reviews and reports.

5.2.1 Statistical analysis' results of the literature

Among the **8 scientific articles studied** from 2001 to 2019 [[48] to [55]], we have identified which risk assessment methods were used. Below is a diagram representing for each method the number of articles in which it is used.

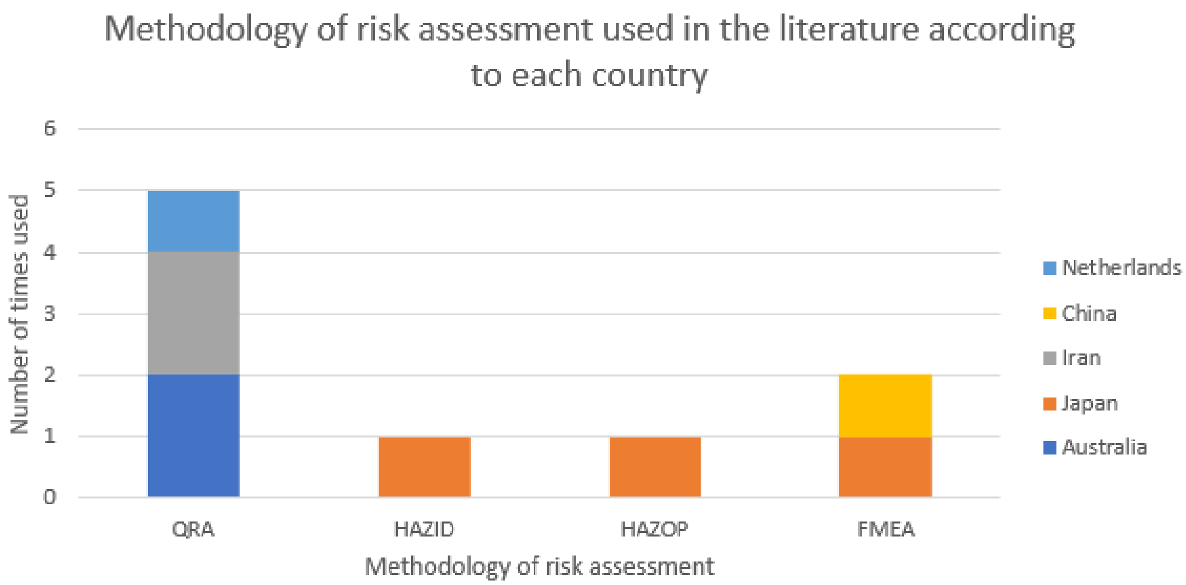


Figure 32 : Distribution of risk assessment methods used for conventional refueling stations in the literature in Japan, Australia, Iran, China and the Netherlands

It should be noted that some articles present several risk assessment methods depending on the purpose and scope of the article. As we can see on the diagram above, the **QRA** method was the most predominant.

In addition, we have highlighted which risk analysis methods have been used in the literature originating from each country. Among the 8 articles studied in the literature, 2 are from Japan, 2 from Australia, 2 from Iran, 1 from China and 1 from the Netherlands. As we can see, the Netherlands, Australia and Iran's scientific articles only present the QRA as their methodology. On the other hand, the Chinese scientific article talks about the use of FMEA methodology and the Japanese scientific articles, the HAZID, HAZOP and FMEA methodologies.

5.2.2 Statistical analysis' results of the consortium members' feedback and the external organizations' reviews and reports.

The statistical sample of data collected from the consortium members' feedback and the external organizations' reviews and reports was unfortunately quite limited. Therefore, it was decided not to plot a diagram that would not be representative. However, it is worth mentioning that the methodologies of risk assessment that are the most commonly used by the consortium members and in the external organizations' reviews and reports are **the QRA, the HAZID and the HAZOP.**

5.2.3 Conclusion on the results of the statistical analysis of risk assessment methodologies for conventional refueling stations

According to the benchmark of the literature and partners best practices, it seems that **QRA is the approach typically used.** Nevertheless**, HAZID and HAZOP** are also commonly used the first steps towards risk management. Indeed, the use of both quantitative and qualitative risk assessment methodologies can allow a comprehensive management of risks related to conventional refueling stations.

In addition, since the HAZOP methodology is mainly focused on the risks specific to a process, it could be a useful method in the case of conventional refueling stations, as the equipment used for each conventional fuel would be specific and different from one fuel to another (e.g. gasoline versus LNG refueling facilities).

5.3 Risk acceptance criteria

Risk acceptance criteria is the parameter which allows the evaluation of risk tolerability.
Depending of the risk assessment methodology, the main criteria used are :

- A risk **matrix** where the risk level of an accident is based on the combination of its severity and its probability of occurrence (e.g. used in FMECA) for qualitative or quantitative risk assessment.
- A **threshold value**, for example, individual risk which represents the risk of an (unprotected) individual dying as a direct result of an on-site accident involving dangerous substances (e.g. 10^{-6} per year is the value of the risk curve in Netherlands used in QRA) for quantitative risk assessment.

During the study of collected data from scientific publications, partners' feedback and industrials' reviews, limited information about risk criteria were found. Nevertheless, the risk matrices presented from Figure 13 to Figure 16 : Rapid Risk Ranking matrix from EIHP project
in Section 4.3.2 are some examples of risk matrices used for risk assessments for a conventional refueling station.

Regarding the threshold value for individual risk, the scientific publications found in the literature and used in the statistical analysis mentions the use of individual or societal risk value when a QRA is used. For example, in some countries, the individual risk criterion is set to 10^{-6}e- death a year. This criterion is commonly used and specified by the regulators/ authorities of some countries (e.g. the Netherlands for process industry in general and Australia for LPG refueling stations [52]).

5.4 Leak frequencies database

In order to determine which are the most commonly used database of leak frequencies in the risk assessment process, we have decided to conduct a statistical analysis on the different sources of information available. The definition of **BEVI/Purple Book** database is given in the section 4.4. In addition, the following definitions are for databases encountered in our statistical analysis of different information sources relating to conventional fuel stations.

The **"Ignition Probability review, model development and look up correlation"** [58] is a document that provides data from the United Kingdom Offshore Operators Association (UKOOA), originating from Health and Safety Executive (HSE) and from the Energy Institute (EI). It was published in January 2006 in the context of a project conducted by ESR Technology (formerly the Engineering Safety and Risk Business of AEA Technology) that aims to improve the modelling of ignition probabilities in onshore and offshore installation.

“DNV Technical note 14” [59] is a report published by DNV on December 2006 which presents failure frequencies for pressure vessels. This Technical Note provides failure frequency data for use in QRAs of process facilities, consisting of generic leak frequencies for each process equipment type, together with frequencies of other failure modes for valves and pumps. For each equipment type, it provides a review of the various available sources of such data, record the details of the analysis of the most useful data, and indicates how the generic values may be modified for specific individual applications. The leak frequencies for the main process equipment items are based on an analysis of the HSE hydrocarbon release database (HCRD) for 1992-2003.

"Loss Prevention in the Process Industries (2nd Edition)" [60] is the second edition of a book that was published in 1996 by Frank P. Lees. This book gives information regarding risk management in the process industries as well as information regarding hazardous scenarios, various equipment, transport, emergency planning and incident investigation. It was written once the importance of loss prevention was underlined by numerous industrial disasters that occurred at the time (e.g. Piper Alpha, Three Mile Island and Chernobyl). The frequencies calculated are extracted from international data from industry (nuclear and chemical plants, refineries, steam plants). It is a compilation of data from different databases (e.g. HSE MARCODE, the Safety and Reliability Directorate (SRD), MHIDAS, FACTS from TNO, etc.).

5.4.1 Statistical analysis’ results of the literature

5 out of the 8 **scientific articles studied** are using leak frequency databases in order to assess the risks quantitatively. The following diagram represents for each database the number of articles in which it is used.

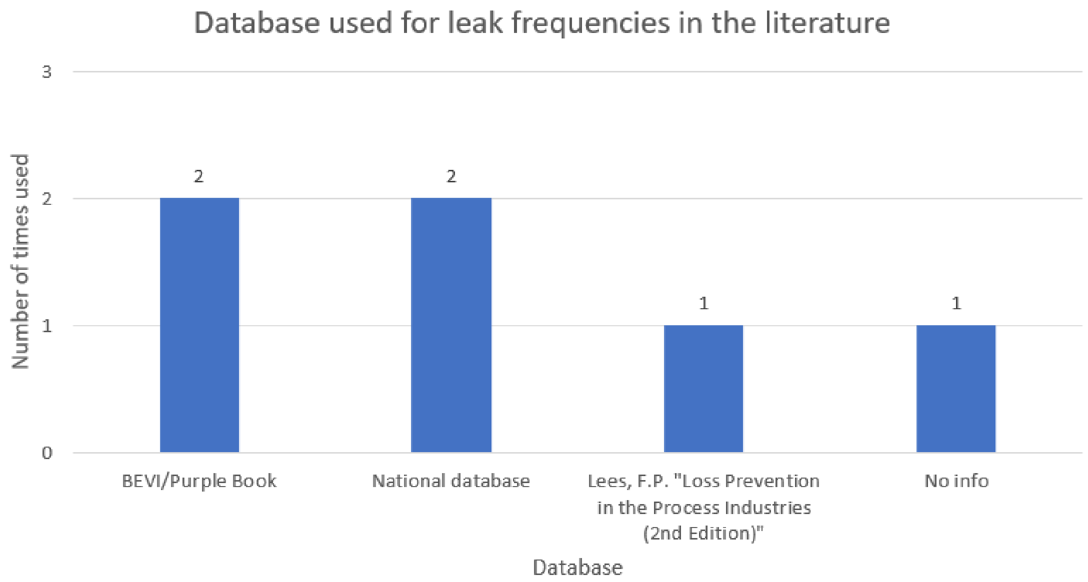


Figure 33 : Distribution of databases of leak frequencies used for conventional refueling station for the 5 articles identified in the literature

It should be noted that some articles use multiple databases. As we can see on the above diagram, the most frequently used databases in our sample are **BEVI/Purple Book and national databases.**

5.4.2 Statistical analysis' results of the consortium members' feedback

The statistical sample of data collected from the consortium members' feedback and the external organizations' reviews and reports is unfortunately quite limited. Therefore, it was decided not to plot a diagram that would probably not be representative. However, it is worth mentioning that the databases of leak frequencies that are the most commonly used by the consortium members and in the external organizations' reviews and reports are **BEVI/Purple Book** [10] **, F.P Lees' "Loss Prevention in the Process Industries" book** [60] **and the DNV Technical note 14** [59].

5.4.3 Conclusion on the results of the statistical analysis of leak frequency databases for conventional refueling stations

The most used databases for leak frequencies in conventional refueling stations' risk assessment is **BEVI/Purple Book**. Moreover, it should be noted that the use of **national databases** is common. Theses databases are set up thanks to the multiple incident reports in the country.

5.5 Modeling tools

This section presents the results of the statistical analysis conducted regarding modeling tools and software used in the risk assessments of conventional refueling stations. The statistical analysis was conducted in two parts. First the analysis of the data extracted from scientific publications and then the analysis of the data extracted from the consortium members' feedback and from the external organizations' reviews and reports. The modeling software used for the following statistical analysis is described in Section **Error! Reference source not found.**.

5.5.1 Statistical analysis' results of literature

Among the scientific publications studied, we collected data regarding the software used for the risk assessment. The following diagram represents for each software the number of articles in which it is used.

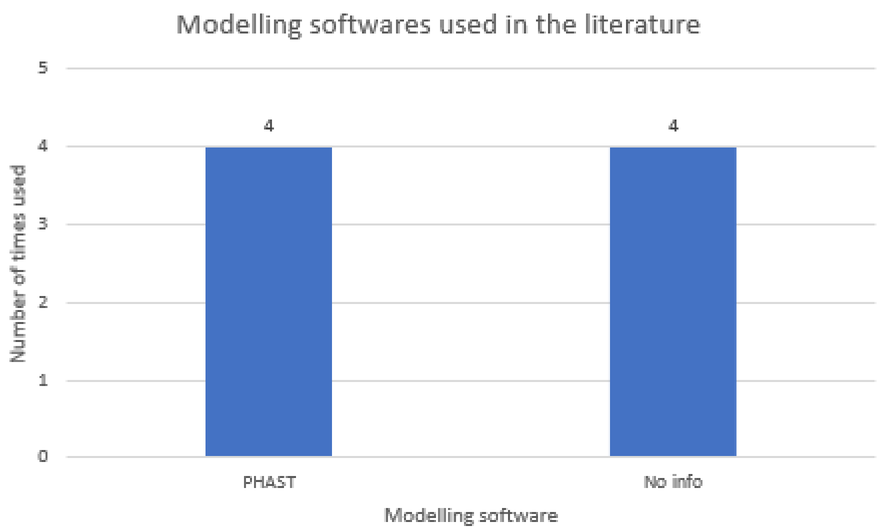


Figure 34 : Distribution of the modeling software used for conventional refueling stations for the 8 articles identified in the literature

As we can see on the diagram, a significant number of the publications do not give information on the modelling software used in their studies. However, among the publications, we can see that those who did give the information on the consequence modelling used, mention only **PHAST as their modelling software**.

One advantage of PHAST is that it allows the modelling of pool spreading and evaporation of LPG or LNG.

5.5.2 Statistical analysis' results of the consortium members' feedback

The statistical sample of data collected from the consortium members' feedback and the external organizations' reviews and reports is unfortunately quite limited and therefore probably not fully representative. Therefore, it was decided not to plot a diagram to show the distribution. However, it is important to note that the modelling software that are the most commonly used by the consortium members and in the external organizations' reviews and reports for conventional refueling stations are **PHAST, FRED and internal tools**.

5.5.3 Conclusion on the results of the statistical analysis of modelling tools

The modelling tools that is currently the most commonly used is **PHAST.** However, some companies and external organizations have developed their own **internal tools**.

One advantage of PHAST is that it allows the modelling of pool spreading and evaporation of LPG or LNG which are the main fuels stored at conventional refueling stations.

5.6 Safety critical scenarios

5.6.1 Introduction

This section presents the results of the statistical analysis conducted regarding the safety critical scenarios that were the mostly used in the risk assessment of conventional refueling stations.

In terms of safety critical scenarios (SCEs), information was collected from the 8 articles of the scientific literature as well as the feedback from the consortium members and the reviews and reports published by external organizations. The information collected are for the scenarios that present the higher risks which means those that are mentioned in the articles are the most frequent and the most hazardous scenarios.

- The main critical scenarios found from the literature are related to three accidental events :Catastrophic ruptures (including burst of capacity)
- Fuel leakage
- Full bore ruptures~

More detailed work on the establishment of the SCEs will be conducted as part of Task 3.5.

The equipment concerned by the **catastrophic ruptures** are the following :

- Fuel delivery trucks
- Fuel storages
- Dispenser

The equipment concerned by the **fuel leakage** are the following :

- Compressors
- Storages
- Dispenser

The equipment concerned by the **full bore ruptures** are the following :

- Fuel delivery trucks
- Pipework
- Dryer
- Valves and fittings

The above list can be helpful for the risk assessments of HRS, however it is not an exhaustive list. A leak of conventional fuel can be very dangerous and lead to phenomenon such as jet fire, pool fire flash fire, BLEVE or explosion. The following dangerous phenomena are common to conventional fuels (except diesel) and can lead to **thermal effects**:

- **Jet fires** occur when the leaking fuel is immediately ignited and creates a continuous flame in the direction of the leakage leading to radiative effects.
- **Flash fires** occur when the ignition of the leaking fuel is not instantaneous. The ignition occurs when the vapor of fuel disperses and are mixed with the surrounding air to create a flammable cloud. Furthermore, the flash fire happens over a very short duration.

The following dangerous phenomena are common to conventional fuels (except diesel) and can lead to **overpressure effects**:

- Unconfined Vapour Cloud Explosion (**UVCE**) when the leaking fuel or vapor of fuel lead to an explosive atmosphere in a unconfined space with delayed ignition
- **Bursting of capacity** due to overpressure inside the equipment

Finally, specific dangerous thermal phenomena are existing for some conventional fuels :

- **Pool fire** in case of spill of diesel, gasoline, LPG, LNG on the floor with ignition
- **BLEVE** of LPG/LNG : capacity under fire leading to its instantaneous burst and formation of a fire ball

5.6.2 Statistical analysis' results of the data from different sources available

We collected data regarding equipment of the conventional refueling stations that are considered in scenarios of higher risk. The following diagram represents the number of times each equipment was mentioned in the different sources available (publications, reviews, reports and feedback from consortium members) and depending on the fuel used in the station studied. It should be noted that diesel was no taken into consideration in this study because of the lack of scientific articles regarding risk assessment for diesel refueling stations. Nevertheless, the scenarios of higher risk regarding diesel are covered by those of gasoline since the diesel major hazard scenarios are of lower consequence compared to gasoline (e.g. flash point).

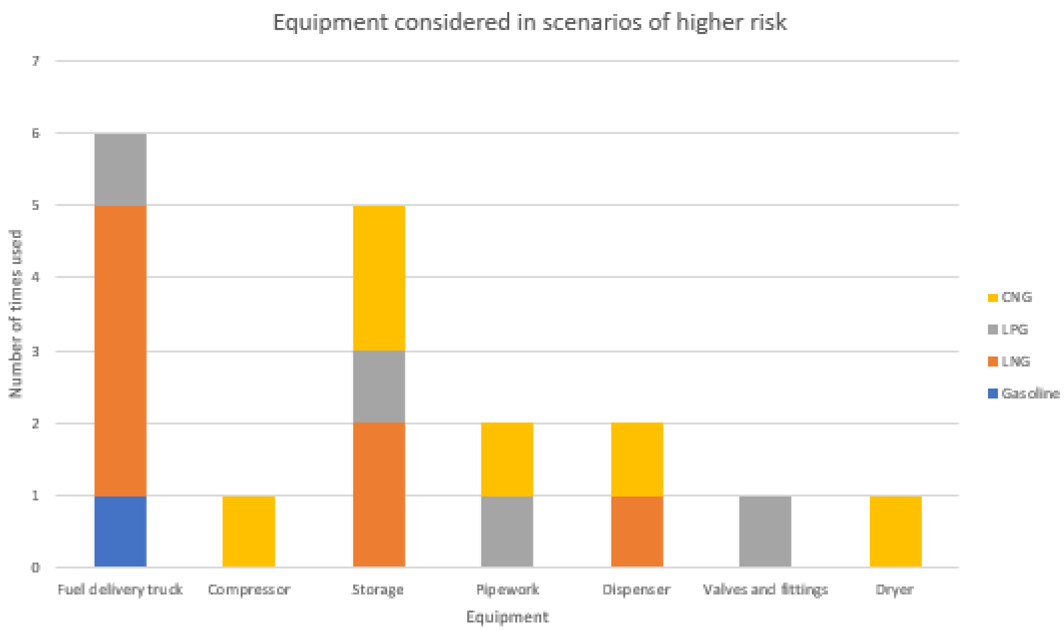


Figure 35 : Distribution of the equipment considered in scenarios of higher risk for conventional refueling stations in the different sources available.

As we can see on the above diagram the equipment with the higher risk of conventional refueling stations are **fuel delivery trucks, storages and dispensers**.

Thus, we focus our statistical analysis on these 3 types of equipment by collecting data on the scenarios of higher risk; and simultaneously compiling information on safety barriers linked to each type of equipment. In addition, the statistical analysis on safety barriers regarding this equipment is presented in the paragraph 5.6.

The following diagram represents the distribution of the 7 scenarios of higher risk identified in the different sources available with regards to the fuel delivery trucks of conventional refueling stations.

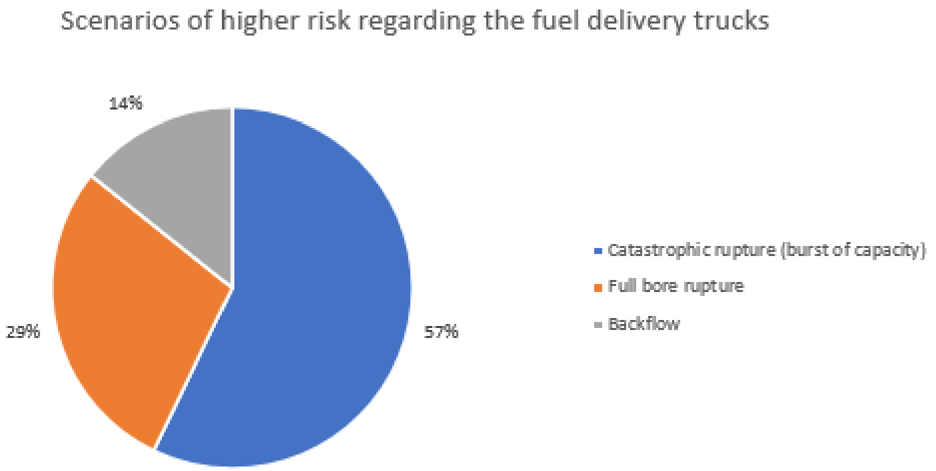


Figure 36 : Distribution of the scenarios of higher risk regarding the fuel delivery trucks of conventional refueling stations in the different sources available.

As we can see on the diagram above, the scenario of higher risk regarding fuel delivery trucks in conventional refueling stations that is the most commonly mentioned in the different sources available is the **catastrophic rupture** of the fuel delivery truck during the fuel unloading operation (e.g. failure of truck leading to the BLEVE of LNG or LPG). The backflow scenario occurs during the fuel unloading operation when the pressure in the storage is higher than the pressure in the fuel delivery truck's tank.

The following diagram represents the distribution of the 6 scenarios of higher risk identified in the different sources available regarding the storage systems of conventional refueling stations.

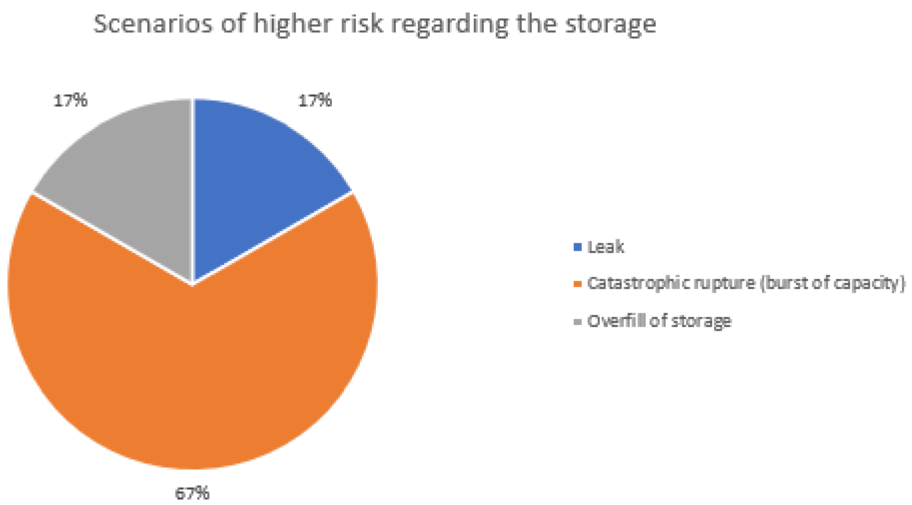


Figure 37 : Distribution of the scenarios of higher risk regarding the storages of conventional refueling stations in the different sources available

As we can see on the diagram above, the scenario of higher risk regarding storages in conventional refueling stations that is the mostly mentioned in the different sources available is **the catastrophic rupture** of the storage (e.g. storage vessel burst). Thus, catastrophic ruptures are considered to be very hazardous events but we also need to be mindful that the frequency of occurrence of this event is very low. It is also important to note that leaks from storage are also regularly mentioned regularly in the different sources of information available.

The following diagram represents the distribution of the 3 scenarios of higher risk identified in the different sources available regarding the dispensers of conventional refueling stations.

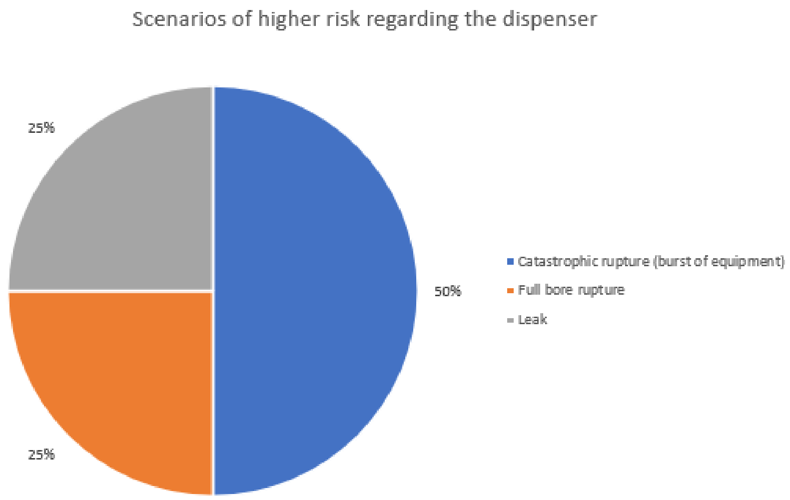


Figure 38 : Distribution of the scenarios of higher risk regarding the dispensers of conventional refueling stations in the different sources available

As we can see in the diagram above, the scenarios of higher risk regarding dispensers in conventional refueling stations that is the most commonly mentioned in the different information sources available is the **catastrophic ruptures** (e.g. failure of hose).

5.6.3 Further information for scenarios of higher risks in a conventional refueling station

In addition to the statistical analysis we conducted above, we should mention that the Hazardous Substance Council in the Netherlands published an advisory report [61] regarding risk calculations and their use for decision making. In this document the **BLEVE** of a fuel delivery truck at a **LPG** filling station is taken as an example by the Council since such incident plays a significant role in external safety policy.

Moreover, the PGS Management Organization, which is a Dutch organization comprising representatives from the authorities, published a report from a Publication Series [62]. This report provides guidance regarding **LNG refuelling stations**. Thus, the scenarios of higher risk used in this report are the following :

- Emission from vent at 10 m height
- 50 mm and 10 mm leak in LNG tank
- 50 mm, 10 mm and 5 mm leak in LNG pipework
- leak in pipe/flange with source strength of 10 g LNG/ s (about 1 mm leak)

In order to complete the information regarding the scenarios of higher risk of conventional refueling stations, it is important to mention the report of INERIS [63] which is a study of hazardous scenarios in conventional refueling stations. In this report, INERIS defined the following five scenarios of higher risk that are the most plausible to occur according to their **analysis of the past accidents on gas station with the following fuels (gasoline, diesel, LPG)**:

- Pool fire scenario due to the accidental spillage of 120 l of gasoline on the distribution area;
- Pool fire scenario due to the deliberate spreading of 960 l of gasoline on the distribution area;
- Fire scenario during the unloading of a tanker truck;
- Fire scenario of cars waiting in line in the area of the service station area;
- Explosion scenario during the unloading of a fuel delivery truck.

Regarding **electrical charging stations**, not enough data was found in the literature in order to conduct a statistical analysis. However, a list of the main risks identified by INERIS [64] regarding fast charging in an electrical charging station has been established below:

- risk of overloading the electrical network, which could lead to local short-circuits, **electrical fires** or a power outage due to excessive and/or simultaneous demands during rapid charging;
- risks of abusive solicitations of the batteries leading to **thermal runaway**, accelerated formation of dendrites;
- risks of ignition due to the simultaneous presence **of ATEX sources and additional ignition sources** (of electrical origin) in the service stations.

5.6.4 Conclusion on the results of the statistical analysis for safety critical scenario in conventional refueling stations

Thanks to the statistical analysis of the data of different sources available we can see that the scenario of higher risk that is the most commonly mentioned is the **catastrophic rupture** of equipment such as **fuel delivery trucks and dispensers** and **leak from storage.**

It is important to consider the scenarios mentioned by INERIS as a scenario of higher risk that is mostly plausible to occur: **pool fire and explosion scenarios from unloading operation** and scenarios of **fire from a vehicle near a dispenser**.

Finally, some national regulations (e.g. Netherlands for LNG stations) specify for specific scenarios to take in consideration : scenarios with **leak size defined on storage/piping/hose which are more probable** scenario than catastrophic rupture scenarios according to the lessons learned.

5.7 Safety barriers

Regarding the safety barriers implemented in a conventional refueling station to manage the risks for the scenarios of higher risk identified in the Section 5.6, we unfortunately did not find enough information in scientific literature, reviews, reports and data collected from the consortium members in order to be able to establish statistics.

Therefore, we decided to list the safety barrier below based on the safety barriers identified in the different available sources and regarding the scenarios of higher risk mentioned in paragraph 5.6.2.

For the **fuel delivery trucks scenario** (catastrophic rupture, full bore rupture and backflow), the safety barriers mentioned are:

- Pressure relief valves
- Emergency Shutdown system
- Non-return valve

For the **storages scenario** (leaks, catastrophic ruptures and overfill storage), the safety barriers mentioned are:

- Emergency shutdown system
- Crash-barrier design around tank
- local and remote ESD well identified and known by workers
- Instructions and signalization for trucks parking related to unloading operation of the fuel delivery trucks

For the **dispensers scenarios** (leaks, full bore ruptures and catastrophic ruptures), the safety barriers mentioned are:

- Break-away coupling
- Crash-barrier design around dispenser
- Shear valve (which shuts off the flow of fuel in case of crash on the dispenser [65])

For **LNG dispensers**, the report from the Publication Series published by PGS Management Organization [62] (a Dutch organization formed of representatives from the authorities) gives recommendations of safety barriers listed below :

- Gas detectors
- Emergency shutdown system
- Temperature detectors near the dispenser and the LNG storage activating the emergency shutdown system.

To sum up, the following table represents the previous safety barriers classified according to INERIS classification [47]:

Name	Active safety barrier	Passive safety barrier	Safety Instrumented Function
Shearvalve		X	
Emergency Shutdown System or Device (e.g. push button leading to a safe automatic actions to shutdown the hydrogen system)			X
Temperature switch (e.g. TSHH leading to an automatic emergency shutdown)			X
Hydrogen detectors or sensors associated to safe automatic actions to shutdown the hydrogen system			X

Breakaway couplings for the flexible hoses	X		
Non return valves	X		
Pressure Relief valves	X		
Crash barrier		X	

Table 14. Non exhaustive list of safety barriers for conventional station for critical scenarios

The instructions, procedures for unloading are not classified as active or passive or SIF barriers as they are relying on human actions. So, they are classified as human/organizational barriers.

5.8 Conclusion of the state of the art of risk assessment on conventional refueling stations

We had insufficient data to achieve a statistical analysis with regards to the practices of the consortium members and the external organizations, but we have managed to do so predominantly using information from scientific literature. We have succeeded in conducting a statistical analysis that allowed us to report on the general practices surrounding risk assessment of conventional refueling stations.

According to the statistical analysis of the risk assessment methods used in the scientific literature as well as the feedback from the consortium members and the reports and reviews of the external organizations, it seems that **QRA is the most commonly used risk assessment methodology**. Most of the time, **HAZID and HAZOP** are also mentioned as first steps towards the risk assessment and management process. Indeed, the use of both quantitative and qualitative risk assessment methodologies allows the comprehensive management of risks related to conventional refueling station.

Furthermore, the statistical analysis allowed us to highlight the databases mentioned in articles and used by partners for leak frequencies for to conventional refueling stations risk assessment. Thus, the data from the **Bevi**/**Purple Book** (non-specific to conventional fuel station) **and national databases** (specific to incidents that occur in conventional refueling stations) are the most mentioned.

Quantitative risk assessment requires consequence modeling tools to determine the extent of potential hazardous events. The statistical analysis revealed that the most commonly used modeling software for the consequence analysis of conventional refueling stations is **PHAST**.

With regards to the scenarios of higher risk, it was determined from the statistical analysis that **fuel delivery trucks, storages and dispensers** are the types of equipment that give rise to scenarios of higher risk. Furthermore, the statistical analysis also shows that **catastrophic rupture** is the most risky and therefore should be studied for fuel delivery truck as well as catastrophic rupture/ leak of/from fuel storage. Nevertheless, this is a deterministic approach (worst case but low likelihood), and new approach (e.g. Netherlands with PGS for LNG [62]) recommend to consider most likely scenarios : leaks scenarios.

Finally, the bibliographic research was very useful in order to establish a non-exhaustive list of safety barriers associated with conventional refueling stations higher risk scenario and safety barriers are listed by equipment.

For **fuel delivery truck** scenarios :

- Gas detector to detect a leak and safely shutdown the system in order to protect equipment and people
- Pressure relief valves to prevent a loss of containment due to overpressure
- Emergency Shutdown system
- Non-return valve

For the **storages scenarios** :

- Gas detector
- Emergency shutdown system
- Crash-barrier design around tank
- local and remote ESD well identified and known by workers
- Instructions and signalization for trucks parking related to unloading operation of the fuel delivery trucks

For the **dispensers scenarios**, the safety barriers mentioned are :

- Gas detector
- Break-away coupling
- Crash-barrier design around dispenser
- Shear valve (which shuts off the flow of fuel in case of crash on the dispenser [65])

These lists could be useful during the development of tasks 3.3/3.4 of the MulHyfuel project (preliminary and detailed risk assessments).

6 Conclusions on the HRS and the conventional refueling stations

Thanks to the data collected regarding HRS and conventional refueling stations, we managed to conduct a statistical analysis surrounding the current state of the art and best practices in scientific literature, as well as the feedback from the consortium members and the reviews and reports of external organizations.

The statistical analysis showed that the risk assessment methods that are the most commonly used are **HAZID, HAZOP and QRA,** in an HRS as well as in a conventional refueling station.

Furthermore, thanks to the statistical analysis we observe that the most commonly mentioned databases for leak frequencies are the **Purple Book for both types of refueling stations.** However, **Sandia National Laboratories' database (HyRAM)** is also used for HRS and the **national databases** (specific to incidents that occurred in conventional refueling stations) are also mentioned for conventional refueling stations.

With regards to the modeling software that are the most commonly used, we observed that **PHAST is the consequence modelling tool** most frequently used for HRS and conventional fuel stations. Due to the specificity of hydrogen, for HRS, **HyRAM** and **internal tools** are also used.

Data on the scenarios of higher risk were also important for the statistical analysis. It was observed that the common critical scenario **are leak on dispensers and storage** for both (HRS and conventional fuel stations). The lessons learned confirm also that these scenarios are among the most frequent scenario. In addition, catastrophic rupture of fuel delivery truck (LPG, gasoline, LNG) and leak on H2 compressor are the additional critical scenario specific to each fuel.

The related common dangerous phenomena for H2 and conventional fuels (except diesel) are:

- **UVCE and flash fire** in case of late ignition of a flammable cloud
- **Jet fire** in case of immediate ignition of the flammable gas released
- **Bursting of capacity** in case of overpressure of vessel

It can be completed by specific dangerous phenomena for each fuel:

- **Pool fire** for LPG, gasoline and diesel in case of fuel spill
- **VCE** in case of hydrogen leak in a confined space leading to explosion in case of late ignition
- **BLEVE** for LNG/LPG storage and fuel delivery truck

Finally, thanks to the bibliographic research, we could establish a non-exhaustive list of safety barriers relating to safety critical scenarios for HRS and conventional fuel station. We can mention the prevention safety barriers to avoid and prevent the loss of containment or bursting of capacity:

- **crash-barrier around equipment** as passive barrier to avoid external aggression (e.g. from vehicle)
- **pressure relief valve** to avoid overpressure in equipment

On the other hand, we can mention the protection safety barriers :

- **gas detectors** and **emergency shutdown** sequency associated to reduce the severity of the leak
- **Emergency Shutdown Device and shut-off valves** associated to reduce the inventory released in case of loss of containment.

7 Recommendations for MultHyFuel's risk assessments

The objective of this deliverable is to identify the best methodology to use in Task 3.3 (preliminary risk assessment) and Task 3.4 (detailed risk assessment). Task 3.3 aims to identify the potential major hazard scenarios and initiators related to H_2 dispenser elements and the scenarios from conventional fuel dispensers. Task 3.4 aims to model the consequences of the representative scenarios identified in T3.3 with available tools typically used for risk assessment for impact on humans & equipment to evaluate the potential severity of these scenarios.

To achieve the objectives and the results of the benchmarking on risk assessment in this deliverable, it is important to take into consideration the environment/layout upon the integration of HRS in existing conventional refueling stations. In accordance with this, it is recommended to follow the following main steps for the next task, Task 3.3:

- Divide the **PFD of the configurations** from deliverable D3.1 into sub systems.

- Select a **representative environment/lay out** for each configuration. Environment and lay out will be studied during the risk assessment in order to evaluate the severity in a multi fuel environment. It will be important to specify the aggressors and key issues to protect in order to take in consideration escalation/dominos effect between H2 and other fuel equipment.

  Pre determine the range of severity with a **H2 quick evaluation tool** to help with ranking of the severity of the H2 scenarios. It will give the safety distances effects (jet fire, LFL distances) for the safety critical scenarios identified in Sections 4.6 and 5.6. It may take the form of figures/tables with safety distances for different H2 pressure and size leaks. These safety distances could be calculated by PHAST or other suitable consequence model.
  Pre-determine the range of frequencies of typical leaks or rupture scenarios related to H2 equipment identified in Sections 4.6 and 5.6. **Likelihood of the typical scenarios (catastrophic rupture, leak, burst)** will be estimated based on the data contained within BEVI/Purple Book and HyRAM (semi quantitative approach) adjusted to the configuration being studied.
  Conduct a **HAZID** (HAZards IDentification) exercise on the configurations identified in task 3.1 with a Rapid Risk Ranking assessment (qualitative / screening approach) to take into consideration the lay out/environment of the multifuel station.
- The Rapid Risk Ranking will be conducted during these screening sessions using the H2 quick severity evaluation tool and estimated likelihood pre-determinated. An example of **Rapid Risk Ranking matrix** from EIHP project [32] is presented in Section 4.3.2 (Figure 16) and can be used for screening

- Define a **risk acceptance criteria** and **rank the scenarios** plotted on the risk matrix in order to identify the higher risk scenarios to be studied in task 3.4 (Detailed risk assessment).

For tasks 3.4 (detailed risk assessment), the scenarios identified as higher risk scenarios in task 3.3 will be assessed quantitatively with respect to their **frequencies and consequences,** according to the following framework:

Achieve a specific review of the **data available for the likelihood evaluation**. It will allow to confirm the relevancy of the databases identified (**HyRAM** and **Bevi/purple book**) compared to what is needed and to identify potential missing data for likelihood evaluation of the critical scenarios identified in task 3.3.

Evaluate the frequencies thanks to the database selected by the review.

Compare the safety distances using **different consequence modeling tools** in order to evaluate the potential severity of these scenarios (impact on humans & equipment) and to validate the tools used for safety distances : **PHAST, CFD tools, FRED, Aldea.**

Evaluate the consequence **with and without safety barriers**.

- Analyse the **dominos effects** between hydrogen dispenser and other fuel dispensers in the multifuel context for each configurations defined in task 3.1 (state of the art about technologies).

Task 3.4 will allow the assessment of the potential risks posed by the safety critical scenarios, thus enabling us to identify the need for additional safety barriers and the knowledge gaps that could be filled by large scale experimentation within WP2.

8 References

[1] International Organization for Standardization, «ISO 31000 Risque management - Guidelines,» 2018.

[2] International Organization for Standardization, «ISO 19880-1:2020 - Gaseous hydrogen - Fuelling stations - Part 1 : General requirements,» 2020.

[3] INERIS, «Formalisation du savoir et des outils dans le domaine des risques majeurs (DRA-35) Ω-7 Méthodes d'analyse des risques générés par une instllation industrielle.,» 2006.

[4] International Electrotechnical Commission, «IEC 31010 Risk management - Risk assessment techniques,» 2019.

[5] International Organization for Standardization, «ISO 17776 - Petroleum and natural gas industries - Offshore production installations - Major accident hazard management during the design of new installations».

[6] CEI, «CEI 61508 : Sécurité fonctionnelle des systèmes électriques/électroniques/électroniques programmables relatifs à la,» CEI, 2010.

[7] CEI, «CEI 61511 : Sécurité fonctionnelle – Systèmes instrumentés de sécurité pour le secteur des industries de transformation,» CEI, 2004.

[8] International Electrotechnical Commission, «IEC 61882 Hazard and operability studies (HAZOP studies) - Application guide,» 2016.

[9] RIVM, « Reference Manual Bevi Risk Assessments (Handleiding Risicoberekeningen Bevi),» 2009.

[10] P.A.M Uijt de Haag et B.J.M Ale, *Guideline for quantitative risk assessment. 'Purple Book'.*

[11] TNO- The Netherlands Organization of Applied Scientific Research, *Methods for calculation of physical effects - due to releases of hazardous materials (liquids and gases) - 'Yellow Book',* C. v. d. Bosch et R. Weterings, Éds., The Hague, 1996.

[12] TNO-The Netherlands Organisation of Applied Scientific Research, *Methods for the determination of possible damage to people and objects resulting from release of hazardous materials - 'Green Book',* Voorburg, 1989.

[13] *Arrêté du 22 octobre 2018 relatif aux prescriptions générales applicables aux installations classées pour la protection de l'environnement soumises à déclaration.*

[14] G. Hye-Ri, S. Seung-Kwon, B. Quang-Vu, H. Daeguen et L. Chul-Jin, «Quantitative risk assessment of an urban hydrogen refueling station,» *International Journal of Hydrogen Energy,* vol. 44, pp. 1288-1298, 8 January 2019.

[15] K. Sun, X. Pan, Z. Li et J. Ma, «Risk analysis on mobile hydrogen refueling stations in Shanghai,» *International Journal of Hydrogen Energy,* vol. 39, pp. 20411 - 20419, 3 December 2014.

[16] A. LaFleur, A.B.Muna et K.M.Groth, «Application of quantitative risk assessment for performance-based permitting of hydrogen fueling stations,» *International Journal of Hydrogen Energy,* vol. 42, pp. 7529-7535, 16 March 2017.

[17] N. Ade, B. Wilhite et H. Goyette, «An integrated approach for safer and economical design of Hydrogen refueling stations,» *International Journal of Hydrogen Energy,* vol. 45, pp. 32713-32729, 13 November 2020.

[18] S. Kikukawa, F. Yamaga et H. Mitsuhashi, «Risk assessment of Hydrogen fueling stations for 70 MPa FCVs,» *International Journal of Hydrogen Energy,* vol. 33, pp. 7129-7136, December 2008.

[19] L. Zhiyong, P. Xiangmincd et MA.Jianxin, «Quantitative risk assessment on 2010 Expo hydrogen station,» *International Journal of Hydrogen Energy,* vol. 36, pp. 4079-4086, March 2011.

[20] L. Zhiyong, P. Xiangmin et M. Jianxin, «Quantitative risk assessment on a gaseous hydrogen refueling station in Shanghai,» *International Journal of Hydrogen Energy,* vol. 35, pp. 6822-6829, July 2010.

[21] J. Nakayama, J. Sakamoto, N. Kasai, T. Shibutani et A. Miyake, «Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station with an on-site hydrogen production system using organic chemical hydride,» *International Journal of Hydrogen Energy,* vol. 41, pp. 7518-7525, 18 May 2016.

[22] P. Russo, A. D. Marco, L. Capobianco et M. Mazzaro, «Quantitative Risk Assessment on a Hydrogen Refuelling,» *CHEMICAL ENGINEERING TRANSACTIONS,* vol. 67, 2018.

[23] K. Tsunemi, T. Kihara, E. Kato, A. Kawamoto et T. Saburi, «Quantitative risk assessment of the interior of a hydrogen refueling station considering safety barrier systems,» *International Journal of Hydrogen Energy,* vol. 44, pp. 23522-23531, 30 August 2019.

[24] T. Suzuki, K. Shiota, Y.-i. Izato, M. Komori, K. Sato, Y. Takai, T. Ninomiya et A. Miyake, «Quantitative risk assessment using a Japanese hydrogen refueling station model,» *International Journal of Hydrogen Energy,* vol. 46, pp. 8329-8343, 11 February 2021.

[25] J. Shi, Y. Chang, F. Khan, Y. Zhu et G. Chen, «Methodological improvements in the risk analysis of an urban hydrogen fueling station,» *Journal of Cleaner Production,* vol. 257, 2020.

[26] M. Hirayama, H. Shinozaki, N. Kasai et T. Otaki, «Comparative risk study of hydrogen and gasoline dispensers for vehicles,» *International Journal of Hydrogen Energy,* vol. 43, pp. 12584-12594, 2018.

[27] T.Skjold, D.Siccama, H.Hisken, A.Brambilla, P.Middha, K.M.Groth et A.C.LaFleur, «3D risk management for hydrogen installations,» *International Journal of Hydrogen Energy,* vol. 42, pp. 7721-7730, 2017.

[28] E. Kim, K. Lee, J. Kim, Y. Lee, J. Park et I. Moon, «Development of Korean hydrogen fueling station codes through risk analysis,» *International Journal of Hydrogen Energy,* vol. 36, pp. 13122-13131, 2011.

[29] X. Pan, Z. Li, C. Zhang, H. Lv, S. Liu et J. Ma, «Safety study of a wind–solar hybrid renewable hydrogen refuelling station in China,» *International Journal of Hydrogen Energy,* vol. 41, pp. 13315-13321, 2016.

[30] «Hydrogen Tools,» [En ligne]. Available: https://h2tools.org/hsp/reviews.

[31] HSE, «Guidance on ALARP Decisions in COMAH - SPC/Permissioning/37,» [En ligne]. Available: https://www.hse.gov.uk/foi/internalops/hid_circs/permissioning/spc_perm_37/.

[32] DNV; the Research Council of Norway; Norsk Hydro ASA;, «Hydrogen applications - Risk acceptance criteria and risk assessment methodology».

[33] N. F. P. Association, NFPA 2 Hydrogen technologies code, USA, 2020.

[34] Norsk Hydro ASA and DNV, *Risk acceptance criteria for Hydrogen Refuelling Stations,* 2003 .

[35] Health and Safety Laboratory; Health and Safety Executive, «Societal Risk : Initial briefing to Societal Risk Technical Advisory Group,» 2009.

[36] J. LaChance, W. Houf, B. Middleton et L. Fluer, «SANDIA REPORT - Analyses to Support Development of,» Albuquerque, New Mexico, 2009.

[37] Japan Nuclear Safety Institute, [En ligne]. Available: http://www.genanshin.jp/english/association/establishment.html.

[38] JANSI-CFR-02, «Estimation of domestic general equipment failure rate considering uncertainty of the number of failures,» 2016.

[39] Nuclear Energy Agency; Organisation for Economic Co-operation and Developmment, «Use and Development of Probabilistic Safety Assessment at Nuclear Facilities,» 2020.

[40] OREDA , [En ligne]. Available: https://www.oreda.com/handbook.

[41] Occupational Health & Safety Information Service, [En ligne]. Available: https://products.ihs.com/ohsis-seo/365791.html.

[42] S. Energy, «HYDROGEN RISK ASSESSMENT MODEL (HYRAM),» [En ligne]. Available: https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/hydrogen-safety-codes-and-standards/hydrogen-risk-assessment-model-hyram/.

[43] Det Norske Veritas (DNV), «QRA software - Safeti,» [En ligne]. Available: https://www.dnv.com/services/qra-software-safeti-1715..

[44] GEXCON, «FLACS-CFD,» [En ligne]. Available: https://www.gexcon.com/products-services/flacs-software/.

[45] D. N. V. GL, «Explosion simulation software - CFD explosion tool - Kameleon FireEx - KFX Exsim,» [En ligne]. Available: https://www.dnv.com/services/explosion-simulation-software-cfd-explosion-tool-kameleon-fireex-kfx-exsim-110661..

[46] J. Sakamoto, R. Sato, J. Nakayama, N. Kasai, T. Shibutani et A. Miyake, «Leakage-type-based analysis of accidents involving hydrogen fueling stations in Japan and USA,» *International Journal of Hydrogen Energy,* vol. 41, pp. 21564-21570, 2016.

[47] INERIS, «ÉVALUATION DE LA PERFORMANCE DES BARRIÈRES TECHNIQUES DE SÉCURITÉ OMEGA 10,» 2018.

[48] G. Ma et Y. Huang, «Safety assessment of explosions during gas stations refilling process,» *Journal of Loss Prevention in the Process Industries,* vol. 60, pp. 133-144, July 2019.

[49] J. Nakayama, J. Sakamoto, N. Kasai, T. Shibutani et A. Miyake, «Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fueling station with an on-site hydrogen production system using organic chemical hydride,» *International Journal of Hydrogen Energy,* vol. 41, pp. 7518-7525, May 2016.

[50] M. Hirayama, H. Shinozaki, N. Kasai et T. Otaki, «Comparative risk study of hydrogen and gasoline dispensers for vehicles,» *International Journal of Hydrogen Energy,* vol. 43, pp. 12584-12594, July 2018.

[51] Y. Liu, Z. Kong et Q. Zhang, «Failure modes and effects analysis (FMEA) for the security of the supply chain system of the gas station in China,» *Ecotoxicology and Environmental Safety,* vol. 164, pp. 325-330, November 2018.

[52] R. E. Melchers et W. R. Feutrill, «Risk assessment of LPG automotive refuelling facilities,» *Reliability Engineering & System Safety,* vol. 74, pp. 283-290, December 2001.

[53] N. Badri, F. Nourai et D. Rashtchian, «Quantitative Risk Assessment to Site CNG Refuelling Stations,» *Chemical Engineering Transactions,* vol. 19, pp. 255-260, 2010.

[54] M. Parvini et A. Kordrostami, «Consequence modeling of explosion at Azad-Shahr CNG refueling station,» *Journal of Loss Prevention in the Process Industries ,* vol. 30, pp. 47-54, July 2014.

[55] A. G. Wolting et L. J. Vijgen, «Development of a QRA method to calculate the risks generated by Liquefied Natural Gas (LNG) filling stations for road trucks,» San Antonio, Texas, 2013.

[56] Det Norske Veritas As, «QRA Study for CNG stations,» Mumbai, 2010.

[57] Idaho National Engineering and Environmental Laboratory, «Qualitative Risk Assessment For An LNG Refuelling Station And Review Of Relevant Safety Issues,» 1999.

[58] Energy Institute, «Ignition Probability review, model development and look-up correlations,» London, 2006.

[59] Det Norske Veritas, «Technical note T14 - Process equipment Failure Frequencies,» 2006.

[60] F. Lees, Lee's Loss Prevention in the Process Industries, Elsevier, 1996.

[61] Hazardous Substances Council - The Netherlands, «Risk calculations by prescription: rituals for granting permits and land-use planning,» The Hague, 2010.

[62] PGS Management Organization, «Natural gas - liquefied natural gas (LNG) delivery installations for vehicles,» 2013.

[63] INERIS, «ETUDE DE SCENARIOS DANGEREUX EN STATION SERVICE,» 2002.

[64] INERIS, «Approche de la maîtrise des risques spécifiques de la filière véhicules électriques - Analyse préliminaire des risques,» 2011.

[65] R. J. Hutchinson et J. S. McSpadden, «FUEL DISPENSER SHEAR VALVE ASSEMBLY,» 2005.

What is MultHyFuel?

The goal of MultHyFuel is to contribute to the effective deployment of hydrogen as an alternative fuel by developing a common strategy for implementing Hydrogen Refueling Stations (HRS) in multi-fuel contexts, contributing to the harmonization of existing laws and standards based on practical, theoretical and experimental data as well as on the active and continuous engagement of key stakeholders.

MultHyFuel is a project funded by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU).

Further information can be found under https://www.multhyfuel.eu.

For feedback on the MultHyFuel project or the published deliverables, please contact info@multhyfuel.eu.

The MultHyFuel Consortium