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Risk Assessment for Industrial Accident Prevention

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Risk Assessment for Industrial Accident Prevention

An Overview of Risk Assessment Methods, Selected Case Studies and Available Software

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Geneva, 2023

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Foreword

Industrial accidents can have devastating impacts on people, the environment and economies. In 2020, an explosion at a warehouse containing some 2,750 tons of ammonium nitrate in the Port of Beirut in Lebanon led to about 300 deaths, 6,500 injuries and 300,000 displaced people. It severely damaged critical infrastructure, including port and healthcare facilities, and residential and commercial areas. This and other major accidents, such as the Toulouse factory explosion in France (2001), Mihăilești explosion in Romania (2004), fertilizer plant explosion in Texas, United States (2013), Tianjin explosion in China (2015) and Bata explosions in Equatorial Guinea (2021), serve as urgent reminders of the need to better understand and apply instruments and tools to assess risks and prevent industrial accidents.

Member States of the United Nations Economic Commission for Europe (UNECE) have developed international legal and policy instruments and tools to support governments, industrial facility operators, experts and the public in strengthening industrial safety. The UNECE Convention on the Transboundary Effects of Industrial Accidents aims to protect people and the environment by reducing the frequency, severity and effects of industrial accidents. It provides measures for the prevention of, preparedness for and response to industrial accidents, including those caused by natural disasters and those with transboundary effects, and for international cooperation amongst its 42 Parties and beyond. The Parties have recognized risk assessment as a crucial element of prevention.

This publication contributes to increasing knowledge on risk assessment for industrial accident prevention in the UNECE region and beyond. Part 1 provides an overview of existing risk assessment methodologies. Decision-makers should consider this overview when selecting a suitable method to be applied. Part 2 presents case studies on the application of different methods. Some of these are transboundary cases that show examples of using risk assessment methods and terminology across borders. As such, this publication offers an exchange of experiences. Readers are encouraged to use this publication for developing effective risk assessments and to ensure risk assessment results are taken into account in siting procedures, safety measures, contingency planning, information to the public and more.

Industrial accident prevention, including through the Convention's implementation and related risk assessment, supports member States in achieving the 2030 Agenda for Sustainable Development. It also contributes to technological disaster risk reduction under the Sendai Framework for Disaster Risk Reduction 2015-2030. I trust this report will serve the UNECE region and beyond to improve industrial safety, enhance transboundary cooperation and protect people and the environment against the effects of industrial accidents.

Tatiana Molcean

Tatiana Molcean
United Nations Under-Secretary-General,
Executive Secretary of the
United Nations Economic Commission for Europe

Background and acknowledgements

This publication was developed under the United Nations Economic Commission for Europe (UNECE) Convention on the Transboundary Effects of Industrial Accidents. The Conference of the Parties to the Convention recognized the importance of risk assessment in the implementation of the Convention. Members of the Convention's Bureau, Working Group on Implementation and secretariat formed a small group on risk assessment and organized, under Switzerland's leadership, the UNECE Seminar on Risk Assessment Methodologies (Geneva, 4 December 2018) to support member States in implementing provisions of the Convention and to facilitate an exchange of information and share experiences in applying risk assessment methodologies. This concluded, among others, with a recommendation to develop a study on risk assessment due to the challenges many countries face in executing transboundary risk assessments and in exchanging knowledge and information on methodologies.

At its eleventh meeting (Geneva and online, 7–9 December 2020), the Conference of the Parties requested the Bureau to determine follow-up activities to the seminar. The small group on risk assessment reconvened and prepared, with the support of a contractor, two reports on: (1) risk assessment methodologies and available software; and (2) case studies on the application of risk assessment methodologies in different countries, to which Estonia, Finland, France, Germany, Hungary, Latvia, Netherlands, Norway, Serbia, Slovenia, Sweden and Switzerland generously contributed. The small group was comprised of: Michael Struckl (Austria), Evgeny Baranovsky (Belarus), Laura Vizbule (Latvia), Sanja Stamenkovic (Serbia), Suzana Milutinovic (Serbia), Jasmina Karba (Slovenia), Martin Merkofer (lead, Switzerland), Raphael Gonzalez (Switzerland) and the secretariat (Claudia Kamke). The group engaged the contractor Jensen Hughes (Jeremy Lebowitz, Purvali Chaudhari and Kamal Aljazireh) to support the preparation of the reports. Financial support for the reports was provided by the Federal Office for the Environment (FOEN) of Switzerland.

At its twelfth meeting (Geneva and online, 29 November–1 December 2022), the Conference of the Parties took note of the reports and mandated the secretariat to publish these as a United Nations publication in the three official UNECE working languages in the biennium 2023–2024. The secretariat prepared the present publication following its work on compiling, reviewing and finalizing the earlier reports. The following UNECE Staff contributed to the reports and/or this publication: Franziska Hirsch, Georgios Georgiadis, Claudia Kamke (led the report development), Yelyzaveta Rubach, Joseph Orangias (led the publication process) and Olga Carlos. The reports were supported by consultant to the secretariat, Max Linsen; and this publication was supported by interns to the secretariat, Eunsong Cho and Giorgia Monsignori. Finally, financial support for this publication was provided by FOEN of Switzerland.

Permission to use the images in this publication was provided by FOEN (Switzerland), Ministry for Ecological Transition and Territorial Cohesion (France), National Directorate General for Disaster Management (Hungary), Norwegian Directorate for Civil Protection (Norway), Risk Analysis Center of the STC Industrial Safety CJSC (Russian Federation) and Swedish Civil Contingencies Agency (Sweden), as well as the American Institute of Chemical Engineers, Chemical Institute of Canada (Major Industrial Accidents Council of Canada), DepositPhotos, Elsevier and Wiley.

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List of Abbreviations and Acronyms

AEGL	Acute Exposure Guideline Level
ALARP/ALARA	As Low as Reasonably Practicable/Achievable
ALOHA	Areal Locations of Hazardous Atmosphere
BLEVE	Boiling Liquid Expanding Vapour Explosion
CA	Consequence Analysis
CFD	Computational Fluid Dynamics
DIPPR	Design Institute for Physical Properties
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ETA	Event Tree Analysis
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects and Critically Analysis
FTA	Fault Tree Analysis
HazId	Hazard Identification
HazOp	Hazard and Operability
IDLH	Immediately Dangerous to Life or Health
LNG	Liquified Natural Gas
LOPA	Layers of Protection Analysis
LPG	Liquified Petroleum Gas
Natech	Natural Hazard-Triggered Technological Disasters
RIVM	National Institute for Public Health and the Environment of the Netherlands
RMP	Risk Management Programme
SIA	Swiss Society of Engineers and Architects
SIS	Safety Instrumented Systems
TNT	Trinitrotoluene
UNECE	United Nations Economic Commission for Europe
VCE	Vapour Cloud Explosion

Executive Summary

The effects of industrial accidents can severely harm people, the environment and economies. As experienced in the past, they have led to fatalities, disease outbreaks, injuries, environmental pollution, biodiversity loss, conflicts, political instability, financial loss and more. National governments and international organizations have developed legal and policy instruments and tools to support the prevention of, preparedness for and response to industrial accidents. The UNECE Convention on the Transboundary Effects of Industrial Accidents is an international legal instrument that obliges its Parties to take safety measures to that effect. As enshrined in Article 6 and Annex V, Parties have recognized risk assessment as a key element of the Convention. This publication was developed to contribute knowledge on risk assessment for industrial accident prevention.

Risk assessment is here defined as the overall process of risk identification, risk analysis and risk evaluation. Numerous risk assessment methodologies exist for measuring and understanding the risks of hazardous activities. Part 1 of this publication presents a general overview of methodologies. While it is not exhaustive, it provides an overview of ones used in the UNECE region. This overview can be useful for more informed decision-making on selecting and developing suitable risk assessment methodologies for different types of facilities and circumstances. Moreover, understanding risk assessment methodologies will ensure that authorities can better consider risk assessment results when making important decisions on the siting of hazardous activities, requirements for safety measures, development of contingency plans, information that should be made available to the public which could be affected by an accident.

To provide a more practical understanding, Part 2 presents eighteen case studies of risk assessment methodologies being applied to industrial facilities. The following Parties to the Convention submitted case studies: Estonia, Finland, France, Germany, Hungary, Latvia, Netherlands, Norway, Serbia, Slovenia, Sweden and Switzerland. The case studies cover risk assessments at five types of facilities: liquified natural gas (LNG)/liquified petroleum gas (LPG) storage tanks; ammonia refrigeration facilities; oil terminals (hydrocarbon loading/unloading/storage facilities); ammonium nitrate storage facilities; and chlorine facilities. Five case studies also provide examples for assessing transboundary risks of industrial facilities, since this has been identified as a challenge for many countries. Furthermore, the Annex lists some software tools that are available to support risk assessment.

In conclusion, risk assessment can support the prevention of industrial accidents and mitigation of their effects should they occur. Understanding the risks of all industrial facilities, including transboundary risks, is essential for developing suitable prevention, preparedness and response measures. Even the safest industrial facility is never totally risk-free. This publication addresses the need for more information and knowledge exchanges on risk assessment. It provides a resource for national authorities, policymakers, operators and anyone with interest to gain a deeper understanding of risk assessments for industrial facilities and to strengthen industrial accident prevention.

Part 1.

Overview of risk assessment methods

I. Introduction, background and scope

The 1992 United Nations Economic Commission for Europe (UNECE) Convention on the Transboundary Effects of Industrial Accidents entered into force in 2000, aiming to help its Parties prevent, prepare for, and respond to industrial accidents, especially those that can have transboundary effects. The Convention fosters transboundary cooperation in industrial accident prevention, preparedness and response among its Parties and beyond, including in countries of Eastern and South-Eastern Europe, the Caucasus and Central Asia beneficiaries of the Convention's Assistance and Cooperation Programme. The workplan will guide the Convention's Parties, non-Parties in the UNECE region, the Bureau, the Working Group on Implementation, the Joint Expert Group on Water and Industrial Accidents (Joint Expert Group) and the secretariat in their activities. Activities are mainly focused on the UNECE region, but can also benefit States members of the United Nations beyond the region, in line with the communication, outreach and engagement strategies.

Risk assessment is an integral part of accident prevention, enshrined in the Convention's provisions (e.g., art. 6 and annex V). An UNECE seminar on risk assessment methodologies (Geneva, 4 December 2018) sought to support UNECE countries in implementing relevant Convention provisions by providing an opportunity to exchange information and share experiences in applying risk assessment methodology. Notable conclusions reached during the seminar included challenges in executing transboundary risk assessment, and the need for more information exchange on risk assessment methodology used in the UNECE region, including available software tools. Accordingly, this report was prioritized among the seminar recommendations.

This report provides a general overview of risk assessment methodology applicable to risks arising from hazardous activities and is not intended to be exhaustive but instead to provide an overview of risk assessment methods used in the UNECE region.

This report is intended to be used in conjunction with the report entitled "Risk Assessment for industrial accident prevention: Selected case studies and available software tools" (hereafter called "Part 2"). Part 2 provides case studies where risk assessment methods were applied to chemical facilities in the UNECE region, including how they apply in a transboundary context. The annex to Part 2 lists some software tools available to support chemical installation risk assessment.

II. Glossary of applicable terminology

This section defines key terms common in the field of risk management, categorized based on the applicable element of risk management (see figure 1).

The following is a list of general terminology:

(a) "Hazard" — The intrinsic property of a dangerous substance or physical situation, with a potential for creating damage to human health or the environment.[1] Hazardous substances are those materials named in annex I to the Convention;

(b) "Hazardous activity" — Any activity in which one or more hazardous substances are present or may be present in quantities at or in excess of the threshold quantities listed in annex I to the Convention, and which is capable of causing transboundary effects;

(c) "Risk" — The likelihood of a specific effect occurring within a specified period or in specified circumstances;[2]

(d) "Individual risk" — The risk to a person near a hazard, including the nature of the injury to the individual, the likelihood of the injury occurring, and the time period over which the injury might occur;[3]

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[1] European Union Seveso-III Directive, art. 3 (14), available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012L0018.

[2] Centre for Chemical Process Safety (CCPS), *Guidelines for Developing Quantitative Safety Risk Criteria* (New York, American Institute of Chemical Engineers (AIChE), 2009).

[3] Ibid.

(e) "Societal risk" — A measure of risk to a group of people, often expressed in terms of the frequency distribution of multiple-casualty events;[4]

(f) "Risk assessment" — Overall process of risk identification, risk analysis and risk evaluation;[5]

(g) "Risk management" — Coordinated activities to direct and control an organization with regard to risk;[6]

(h) "Stakeholder" — Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity;[7]

(i) "Transboundary effects" — Serious effects that have an impact across the border with another country, generally linked to human health and the environment.

The following is a list of terminology related to risk and hazard identification:

(a) "Hazard analysis" — The identification of individual hazards of a system, determination of the mechanisms by which they could give rise to undesired events, and evaluation of the consequences of these events on health (including public health), environment and property;[8]

(b) "Hazard identification" — The identification of risk source(s) capable of causing adverse effect(s)/event(s) to humans or the environment species, together with a qualitative description of the nature of this/these effect(s)/event(s);[9]

(c) "Hazard and Operability Study (HazOp)" — See subsection B.3.2;

(d) "Initiating cause/event" — The operational error, mechanical failure, or external event that is the first event in an incident sequence and that marks the transition from a normal to an abnormal situation;[10]

(e) "Loss event" — Point of time in an abnormal situation when an irreversible physical event occurs that has the potential for loss and harm impacts;[11]

(f) "Loss of containment event" — An event when hazardous substances are released, such as through a leak or rupture of piping systems, atmospheric or pressurized tanks; can be immediate or continuous in time;

(g) "Risk identification" — Process of finding, recognizing, and describing risks;[12]

(h) "What-if" — See subsection B.3.1.

The following is a list of terminology related to risk analysis:

(a) "Risk analysis" — Process to comprehend the nature of risk and to determine the level of risk;[13]

(b) "Risk analysis categories", comprising:

    i. "Qualitative risk analysis" — Based primarily on description and comparison using historical experience and engineering judgment, with little quantification of the hazards, consequences, likelihood, or level of risk;[14]

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[4] Ibid.

[5] International Organization for Standardization (ISO), ISO Guide 73:2009(en) Risk management – Vocabulary (2009).

[6] Ibid.

[7] Ibid.

[8] CCPS, *Guidelines for Hazard Evaluation Procedures: Third Edition* (New York, AIChE, 2008).

[9] European Commission. "First Report on the Harmonization of Risk Assessment Procedures. Part 2: Appendices", Health and Consumer Protection Directorate-General. 26–7 October 2000.

[10] CCPS, *Guidelines for Hazard*.

[11] Ibid.

[12] ISO, ISO Guide 73:2009(en).

[13] Ibid.

[14] CPPS, "CCPS Process Safety Glossary", available at www.aiche.org/ccps/resources/glossary?page=1.

ii. "Semi-quantitative risk analysis" — Includes some degree of quantification of consequence, likelihood, and/or risk level;[15]

iii. "Quantitative risk analysis" — The systematic development of numerical estimates of the expected frequency and severity of potential incidents associated with a facility or operation based on engineering evaluation and mathematical techniques;[16]

(c) "Computational fluid dynamics models" — A class of models that can simulate very highly resolved, three-dimensional, time-dependent distributions of wind and liquid flows and material concentrations. These models generally solve the basic equations of motion and conservation using very small grid spacings and time steps and are computer intensive;[17]

(d) "Consequence assessment/analysis" — The process of determining and quantifying adverse effects caused by exposures to a risk agent, independent of frequency or probability;

(e) "Domino effects" — The triggering of secondary events, such as toxic releases, by a primary event, such as an explosion, such that the result is an increase in consequences or area of an effect zone. Generally only considered when a significant escalation of the original incident results;[18]

(f) "Event tree" — A logic model that graphically portrays the combinations of events and circumstances in an incident sequence;[19]

(g) "Failure modes, effects (and criticality) analysis (FMEA/FMECA)" — See subsection 2.3.3;

(h) "Fault tree" — A logic model that graphically portrays the combinations of failures that can lead to a specific main failure or incident of interest (top event);[20]

(i) "Frequency" — Number of events or outcomes per defined unit of time;[21]

(j) "Frequency analysis" — A process by which the rate of occurrence of an adverse event is determined;

(k) "Layers of Protection Analysis (LOPA)" — See subsection B3.5;

(l) "Probability" — Measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty;[22]

(m) "Release models" — A model representing the mass and/or energy transport associated with a release from containment of material and/or energy and the environment wherein it happens;

(n) "Safety systems" — Equipment and/or procedures designed to limit or terminate an incident sequence, thus mitigating the incident and its consequences;[23]

(o) "Scenario" — A detailed description of an unplanned event or incident sequence that results in a loss event and its associated impacts, including the success or failure of safeguards involved in the incident sequence.[24]

The following is a list of terminology related to risk evaluation:

(a) "Risk evaluation" — Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable;[25]

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[15] Ibid.
[16] CCPS, *Guidelines for Hazard*.
[17] CPPS, "CCPS Process Safety Glossary".
[18] Ibid.
[19] CCPS, *Guidelines for Hazard*.
[20] Ibid.
[21] ISO, ISO Guide 73:2009(en).
[22] Ibid.
[23] CCPS, *Guidelines for Hazard*.
[24] CPPS, *Guidelines for Investigating Process Safety Incidents: Third Edition*, (New York, AIChE, 2019).
[25] ISO, ISO Guide 73:2009(en).

(b) "Risk criteria" — Terms of reference against which the significance of a risk is evaluated.[26] Risk criteria are based on organizational objectives, external and internal context. They can be derived from standards, laws, policies and other requirements:

   i. "Societal risk criteria" — Risk criteria applied to a group of people and those who may not be in the direct vicinity of a hazard;

   ii. "Individual risk criteria" — Risk criteria applied to the individual in the vicinity of a hazard;

   iii. "Cost-benefit criteria" — Risk criteria developed as a means of defining a level at which the cost of implementing additional risk reduction measures grossly outweighs the benefits achieved by those measures.

III. Overview of risk management process

Industrial facilities can be exposed to risks that may have an impact on personnel, property, the public and the environment and are often inherent due to the nature of operations conducted, hazards of materials stored, characteristics of processes, or even inadequate management systems. To address these issues, a systematic approach is typically employed to allow stakeholders to identify, evaluate and control risks. Section 3 below provides an overview of risk management concepts, specifically focusing on the risk assessment component.

The broader risk management process provides a framework and structured method that allows operators to understand the risks related to industrial hazardous activities and reach acceptable levels of risk by implementing adequate prevention and/or mitigation measures. First, the scope of the risk management process must be defined, including the purpose and objectives of the study. The baseline conditions, limitations, inputs and outputs of the risk management process must be clearly described, including considerations for the following: facility or process design, natural hazards, intentional acts, human errors, mechanical failures, off-site hazards, environmental effects, domino effects and emergency response effectiveness. Risk management is divided into three sequential components supplemented by feedback loops and continuous communication with stakeholders (see figure 1):

(a) "Risk assessment" comprises three steps:

   i. "Risk identification" to identify hazards and characterize risks presented by those hazards;

   ii. "Risk analysis" to measure the elements of the identified risks in terms of consequence severity and likelihood of occurrence;

   iii. "Risk evaluation" to determine if the risks are acceptable to stakeholders based on a predetermined level of risk tolerance;

(b) "Risk control" determines preventative and/or mitigative risk reduction measures, implemented at various levels (e.g., engineering controls for a process or implementing a process safety management programme) to reduce the likelihood of failure events and/or the severity of a consequence. Risk reduction measures then feed back into the risk assessment step where scenarios are re-evaluated. Once the risks are determined to be acceptable, the process continues;

(c) "Risk review" provides the means for continuous improvement by monitoring and auditing risks. Post-incident investigations and lessons learned, leading and lagging indicators, improvement of personnel training programmes, and program audits can be used to guide further risk reduction or risk acceptance modifications.

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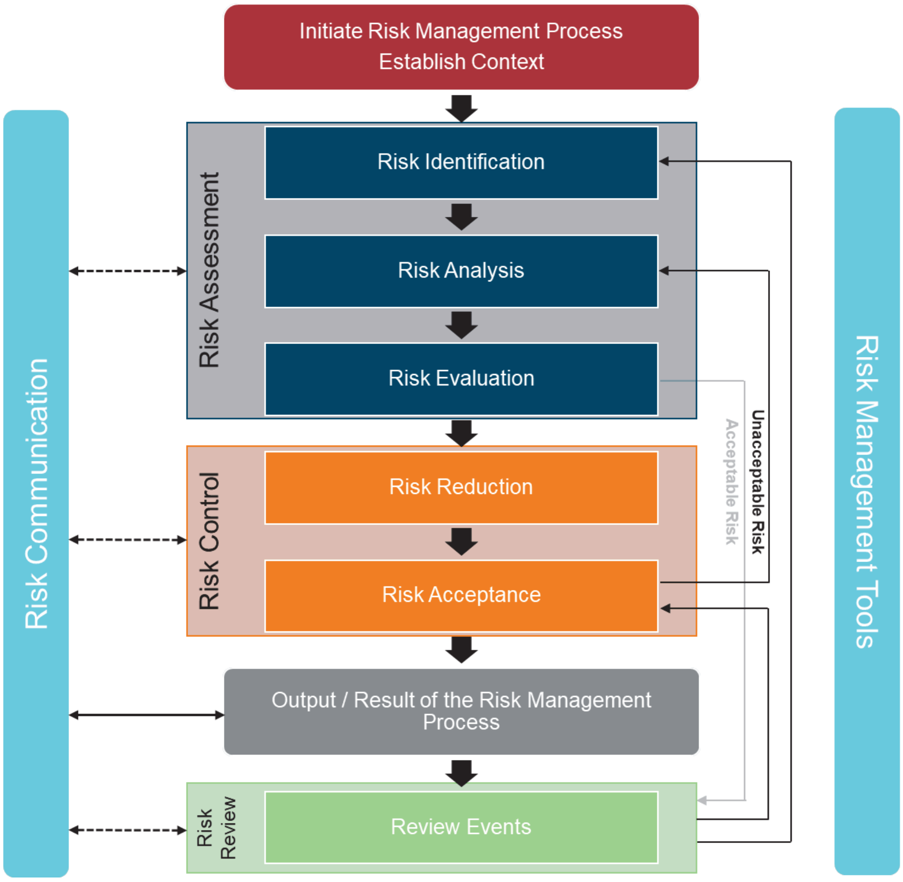
[26] Ibid.

Figure 1.
Overview of risk management process



Source: Created by author of present report.

Note: The terms used in figure 1 are defined differently across organizations/entities; thus, there may be discrepancies between the reader's understanding and the way these terms are used in this report[27] (see figure 1 and section B for clarification).

This document focuses on the risk assessment stage and its three steps of identification, analysis and evaluation, but does not cover other stages/elements contained in figure 1.

Lastly, the risk assessment process is overlaid on baseline design standards that vary by country. Minimum safety standards must be respected before introducing risk assessment; however, the level of safety achieved by complying with codes and standards will similarly vary by country. Thus, understanding the context of the risk assessment is critical to enable comparisons from different stakeholders in a transboundary context. Multiple stakeholders can have widely varying opinions on "acceptable risk". Harmonized evaluation criteria should be: a long-term goal of transboundary cooperation; consistent across stakeholder types; and applicable for all chemical installations.

IV. General introduction to risk assessment methodology

This report focuses on the first component of risk management: risk assessment. Broadly speaking, risk assessment encompasses control of hazardous processes; the scope of this document is limited to control of acute effects from catastrophic releases of hazardous substances (defined in Convention, annex I) in general and, if possible, also in a transboundary context. The purpose of risk assessment

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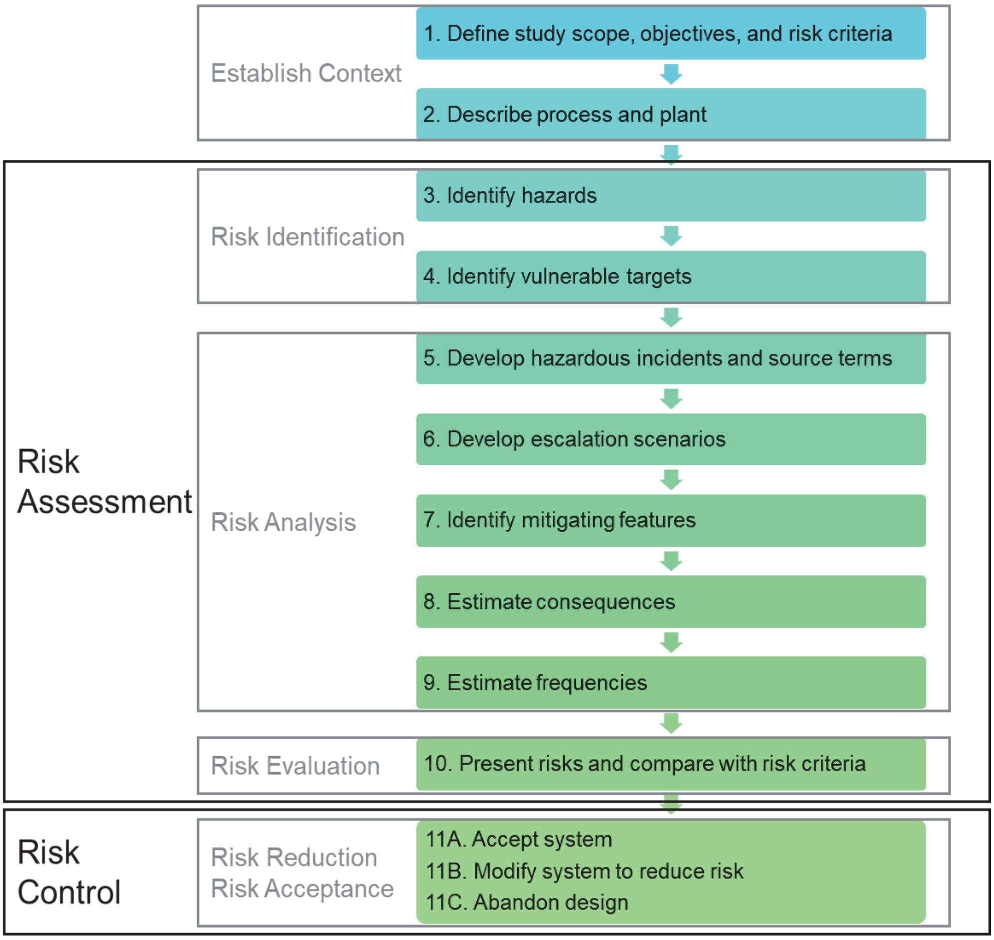
[27] Ibid.; European Commission, "First Report"; and Frans Møller Christensen and others, "Risk terminology - a platform for common understanding and better communication", *Journal of Hazardous Materials*, vol. 103, No. 3 (2003), pp. 181–203.

is to evaluate hazards and eliminate or reduce the level of its risk through preventative and/or mitigative control measures. Preventative hazard controls, such as elimination or substitution of a hazardous material or process, are generally preferred; when a hazardous material is eliminated, loss of containment of that material need not be included in the risk assessment. While effective, elimination or substitution tend to be difficult for existing processes or facilities.[28]

Figure 2 describes the risk assessment process in detail, including preceding and subsequent steps (under “Establish context” and “Risk control” in figure 1, respectively).

Figure 2.
Risk assessment process



Source: Adapted from Sam Mannan (ed.), *Lees' Loss Prevention in the Process Industries* (4th edition, Elsevier 2012) 291.

Risk assessments should begin with the following steps to establish context: define the purpose and scope of the assessment, engage with stakeholders, define objectives, consider human, organizational and social factors, and review risk criteria for decisions.[29]

Three components of risk assessments will be discussed in detail in this section: risk identification, risk analysis and risk evaluation. This structure also follows the format of International Electrotechnical Commission 31010.[30] This section details methods available to execute analysis and

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[28] Many sources, including United States National Institute for Occupational Safety and Health, see /www.cdc.gov/niosh/topics/hierarchy/default.html.

[29] International Electrotechnical Commission (IEC)/ISO, IEC 31010:2019(en) Risk management — Risk assessment techniques (2019).

[30] Ibid.

evaluation as described in annexes IV–VI of the Convention, and to strengthen risk governance as one of the objectives of the Convention's long-term strategy until 2030 (ECE/CP.TEIA/38/Add.1).

A. Risk identification

After stakeholders initiate the risk management process and establish context, the first step in executing a risk assessment is to clearly and comprehensively identify the hazards and potential damage receptors present at or affecting a subject facility. It is important that stakeholders identify risks, regardless of whether their sources are under the stakeholders' control.[31] In figure 2, the risk identification step (items 3 and 4) establishes the basis for the risk assessment.

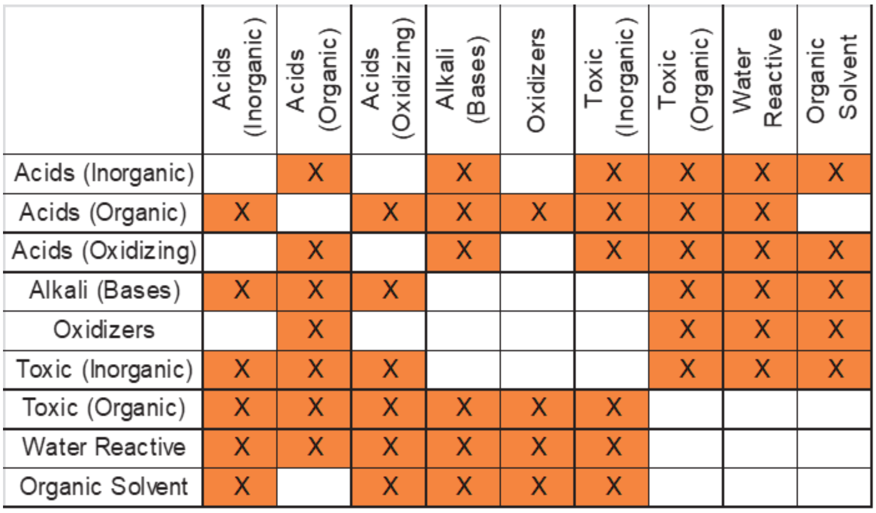
1. Understanding chemical and physical hazards

Hazard identification corresponds to figure 2, item 3. The first step in hazard identification is to determine and document the characteristics and quantities of hazardous substances used at a facility; for example, raw materials, intermediates and finished products. Characteristics to consider include the nature of hazard (health, physical environmental) and other relevant properties (e.g., vapour density, boiling point, flammability, corrosivity, toxicity and reactivity). Safety data sheets generally contain this information, but are not always comprehensive, particularly when evaluating chemical reactivity concerns (safety data sheets may not include specific combinations of chemicals). Additional relevant resources include government or public databases, published literature, or commercially available software or databases; for example, the Design Institute for Physical Properties database is a comprehensive, widely used reference.[32] Examples of common tools for hazard identification are interaction matrices and checklists.

1.1. Interaction matrix

The interaction matrix is a simple tool to assist in identifying process hazards by analysing cases of incompatibilities in the facility. Specific parameters such as hazardous substances, process conditions and environmental factors are listed on two axes.[33] The matrix is then completed by defining the consequences of combinations of parameters (e.g., chemical A mixed with chemical B or chemical A at a high temperature).

Table 1.
Example chemical incompatibility matrix



	Acids (Inorganic)	Acids (Organic)	Acids (Oxidizing)	Alkali (Bases)	Oxidizers	Toxic (Inorganic)	Toxic (Organic)	Water Reactive	Organic Solvent
Acids (Inorganic)		X		X		X	X	X	X
Acids (Organic)	X		X	X	X	X	X	X	
Acids (Oxidizing)		X		X		X	X	X	X
Alkali (Bases)	X	X	X				X	X	X
Oxidizers		X					X	X	X
Toxic (Inorganic)	X	X	X				X	X	X
Toxic (Organic)	X	X	X	X	X	X			
Water Reactive	X	X	X	X	X	X			
Organic Solvent	X		X	X	X	X			

Source: Created by author of present report.

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[31] ISO, ISO 31000:2018(en) Risk Management – Guidelines (2018).

[32] Government of Flanders (Belgium), *Risk Calculations Manual: Guidelines for quantitative risk analysis, indirect risks and environmental risk analysis – Version 2.0 of 1 April 1 2019* (Brussels).

[33] CCPS, *Guidelines for Hazard*.

Note: Table 1 lists incompatibilities between chemical classes; when applied to a facility or a process, the matrix could be more specific to indicate expected reactions and results of incompatibility (e.g., exothermic reaction leading to release of flammable gases). This simple qualitative measure is inherently limited but can be useful as an early hazard identification tool.

1.2. Checklist

Another basic hazard identification method is a checklist, which uses a developed list of questions addressing the facility or process hazards for a team to work through. To be comprehensive and effective, the questions are usually specific to a facility or process and provide a consistent and thorough basis for identifying hazards. Examples of questions that may be used during a checklist analysis include whether: (a) the material is flammable and the flashpoint is below the temperature at which the process operates; (b) the material will present a toxic inhalation hazard to occupants beyond the site boundary if released into the atmosphere; and (c) the ingredients could present a reactivity hazard when introduced into the batch reactor. Although checklists can be an effective hazard identification tool, they often cannot anticipate all hazardous situations and upset conditions that could lead to a hazard. When using this method, questions should be adaptable and able to incorporate insights and necessary modifications from the review team to ensure that conditions of specific facilities are duly considered.

2. Identify vulnerable targets

Common vulnerable targets for chemical facility risk assessments may include employees, off-site public and environmental receptors (including potential transboundary effects).

3. Results of risk identification step

The results of the risk identification step are used as inputs to the next step, risk analysis. Typical risk identification results include both chemical and process hazards. Results from each of the items listed below are required to proceed to the next step, risk analysis:

(a) List of quantities and hazard classes of hazardous substances;

(b) Possible chemical reactivity hazards due to chemical mixing;

(c) Natural hazards affecting the establishment;

(d) Physical hazards associated with a process or facility, such as high pressure or temperature;

(e) General understanding of possible scenarios leading to loss of containment;

(f) List or map of vulnerable targets.

B. Risk analysis

Following risk identification for a system or facility, the next step is to define the risk related to the associated hazards through a risk analysis. The objective is to define the frequency or probability of an event (such as a fire or explosion) and the level of consequence or severity associated with that event. Throughout the risk analysis step, both prevention and mitigation should be considered. This section reviews several methods and tools available for executing a risk analysis that vary in terms of the degree of detail, the purpose of the analysis and required data.[34]

1. Risk analysis process

A risk analysis is typically based on scenarios formulated at the risk identification stage. These scenarios centre on selected loss of containment events and aim at developing accidental sequences from major causes (mechanical failure, human failure) to expected major effects (fire, explosion, toxic release) and damage to human health and the environment.

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[34] Karmen Poljansek and others, *Recommendations for national risk assessment for disaster risk management in EU: approaches for identifying, analysing and evaluating risks – version 0* (Luxembourg, Publications Office of the European Union, 2019).

To assist with scenario selection, the European Commission Joint Research Centre has worked with industry to develop a handbook with typical recommended scenarios for many common materials (flammable liquids, liquified natural gas, anhydrous ammonia, etc.).[35]

The number and detail of scenarios vary based on the risk analysis method used. For qualitative and semi-quantitative risk analysis methods, stakeholders may consider many scenarios leading to undesirable events. However, quantitative risk analysis methods may consider a limited number of scenarios that must be well defined for further analysis (e.g., worst-case credible scenarios). A numerical calculation approach must be completed for each identified scenario. If the results are in a common set of units (e.g., potential loss of life per year, injuries per year, amount of surface water or groundwater polluted per year), they can be added to get overall values for a population of receptors over many individual scenarios.

For quantitative risk analysis methods, the scenario selection must be taken a step forward. A source term is defined that describes the release scenario by estimating discharge rates and total quantity released.[36] When developing the source term, it is critical to define the release phase, type of release (pipe break, accidental spill, etc.), and leak duration. Common source terms to be considered and the methods for conducting the calculations are defined in published resources (e.g., Committee for the Prevention of Disasters "Yellow Book" [37] or Guidelines for Chemical Process Quantitative Risk Analysis).[38]

2. Risk analysis methods

Numerous risk analysis methods are used at different stages of the process. Process hazard identification tools, such as What-if checklists and HazOp, are typically aimed at determining all potential scenarios on a particular site. A second set of risk analysis tools is used to examine control measures and likelihood, such as LOPA and Fault Tree Analysis (FTA). These methods are applied to selected scenarios to determine whether control measures are sufficient, and in the case of quantitative or semi-quantitative analysis, to assign likelihood.

Risk analysis methods can be qualitative, semi-quantitative or quantitative, as explained further in this section. Risk analysis methods can be further substantially subdivided based on the type of output/result:

(a) Deterministic methods are built upon a finite hazard scenario to determine the consequences for people and the environment given a set of defined circumstances. Consequently, these methods do not account for the probability of all possible outcomes but rather focus on a selected scenario, such as the worst-case event or most likely event to occur;[39]

(b) Probabilistic methods are based on the probability of a particular failure scenario occurring (usually equipment failure) and the probability of various consequences.[40] These methods can therefore capture the probability of many scenarios leading to undesirable outcomes.

The availability of a variety of risk analysis methods gives flexibility to the user depending on the complexity of the facility and availability of process/facility details at the time of the analysis. This section presents risk analysis methods commonly used in the process industries. As there are many variations and hybrid approaches, this list is not exhaustive.[41] A typical risk analysis may use a combination of qualitative and quantitative methods; for example, a site may often start with a

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[35] Michael Struckl, *Handbook of Scenarios for Assessing Major Chemical Accident Risks* (Luxembourg, Publications Office of the European Union, 2017).

[36] CPPS, *Guidelines for Chemical Process Quantitative Risk Analysis: Second Edition* (New York, AIChE, 1999); and X.Seguí and others, "Methodology for the quantification of toxic dispersions originated in warehouse fires and Its application to the QRA in Catalonia (Spain)", *Journal of Loss Prevention in the Process Industries*, vol. 32 (November 2014), pp. 404–414.

[37] C.J.H. van den Bosch and R.A.P.M. Weterings, eds., *CPR 14E – Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases) – "Yellow Book"* (The Hague, CPR, 1996).

[38] CPPS, *Guidelines for Chemical*.

[39] Poljansek, *Recommendations*.

[40] J. Tixier and others, "Review of 62 risk analysis methodologies of industrial plants", *Journal of Loss Prevention in the Process Industries*, vol. 15, No. 4 (July 2002), pp. 291–303.

[41] Mannan, *Lees' Loss*.

qualitative method to identify all possible scenarios and then use additional quantitative methods to study particular scenarios in-depth.

2.1. Qualitative methods

Qualitative risk analysis methods are typically the least complex as they do not require the use of calculations, computer modelling, or databases for failure frequencies. These methods are used to establish a baseline understanding of risks for a particular process or facility and assist in determining systems or equipment that may need further analysis using a more detailed method. Because of their inherent nature, which is based on review team members' expertise, qualitative methods can be limited in their ability to accurately represent risks.

2.2. Semi-quantitative methods

Semi-quantitative risk analysis methods employ some degree of quantification of consequence, likelihood and/or risk level; are typically used when stakeholders require additional depth in quantifying failure scenarios and consequences but do not necessarily need or have the means to employ a fully quantitative risk analysis; may be sufficient for facilities where the hazards may not pose a significant risk on-site and/or off-site; and have some similar limitations to qualitative methods, such as relying on expert judgment, but provide the ability for risk to be quantified in relative terms, thus allowing for a more enhanced risk evaluation, the next step in risk assessment.

2.3. Quantitative methods

Unlike qualitative methods, quantitative risk analysis methods include the use of numerical estimates of severity and likelihood or frequency of a loss of containment event. Quantitative risk analysis methods require more rigour in their development and execution. Quantitative methods involve multiple steps, including development of scenarios and source terms, analysing consequences from the selected scenarios, determining the probability or frequency of failures leading to the selected scenarios, and considering the effects of existing safeguards in place to prevent or mitigate the analysed scenarios.

3. Risk analysis tools

In most cases, use of multiple risk analysis tools is necessary to address all steps of risk analysis indicated in figure 2 (see table 5 for summary). Several tools are described in detail below.

3.1. What-if or What-if/Checklist

The What-if framework provides a pre-populated, scenario-based list of questions used for initial process hazard identification to identify hazards and potential loss of containment scenarios. A review team addresses these questions and provides detailed answers with the aim of developing recommendations to prevent or mitigate the loss of containment scenario (see table 2 for example of a What-if method). The procedure of the What-if method renders it more likely to reveal unique process hazards than a basic checklist. However, the method is limited by the experience of the review team members. To alleviate this limitation, this tool can be used in combination with the checklist to facilitate a more thorough and informed analysis.[42]

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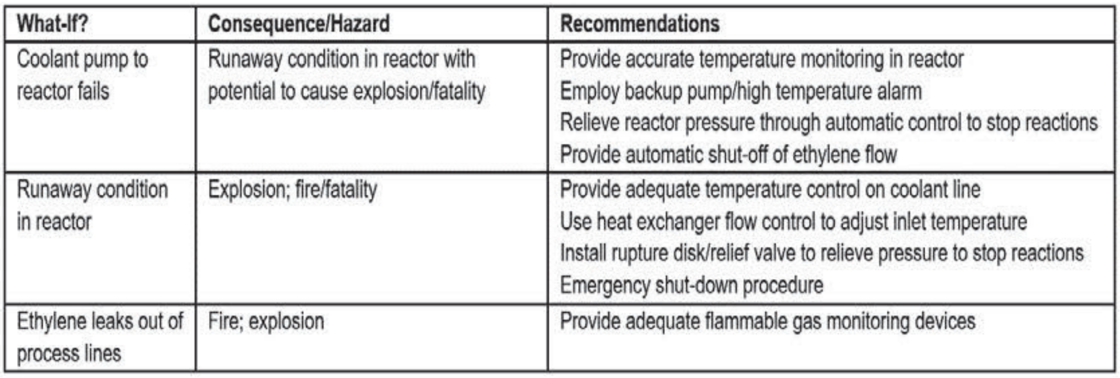
[42] CCPS, *Guidelines for Hazard*.

Table 2.
What-if or What-if/Checklist: results for a high-pressure, low-density polyurethane plant



What-If?	Consequence/Hazard	Recommendations
Coolant pump to reactor fails	Runaway condition in reactor with potential to cause explosion/fatality	Provide accurate temperature monitoring in reactor Employ backup pump/high temperature alarm Relieve reactor pressure through automatic control to stop reactions Provide automatic shut-off of ethylene flow
Runaway condition in reactor	Explosion; fire/fatality	Provide adequate temperature control on coolant line Use heat exchanger flow control to adjust inlet temperature Install rupture disk/relief valve to relieve pressure to stop reactions Emergency shut-down procedure
Ethylene leaks out of process lines	Fire; explosion	Provide adequate flammable gas monitoring devices

Source: Adapted from Sam Mannan (ed.), *Lees' Loss Prevention in the Process Industries* (4th edition, Elsevier 2012) 233.

3.2. Hazard and Operability

A HazOp is a systematic review of hazards associated with a facility, used by the chemical process industry worldwide. The facility is subdivided into manageable systems and subsystems, called nodes. Possible deviations from normal operation within these subsystems are studied by a multidisciplinary team. Piping and instrumentation diagrams for the process are examined systematically to determine abnormal causes and adverse consequences for all plausible deviations.[43] The HazOp method is represented in figure 3.[44]

A series of guide words and parameters are used in combination and create hypothetical deviations from normal operation (e.g., no flow into the process or high temperature in a reactor). Examples of these deviations are shown in table 3.

Table 3.
Hazard and Operability workshop guidewords for scenario development

Guide Word	*Meaning*	*Parameter*	*Deviation*
None	Negation intention	Flow	No flow
		Level	Zero level
Less	Quantitative decrease	Flow	Low flow rate
		Level	Low level
		Temperature	Low temperature
		Pressure	Low pressure
		Concentration	Low concentration
More	Quantitative increase	Flow	High flow rate
		Level	High level
		Temperature	High temperature
		Pressure	High pressure
		Concentration	High concentration
Reverse	Logical opposite	Flow	Reverse flow rate
		Pressure	Reverse pressure

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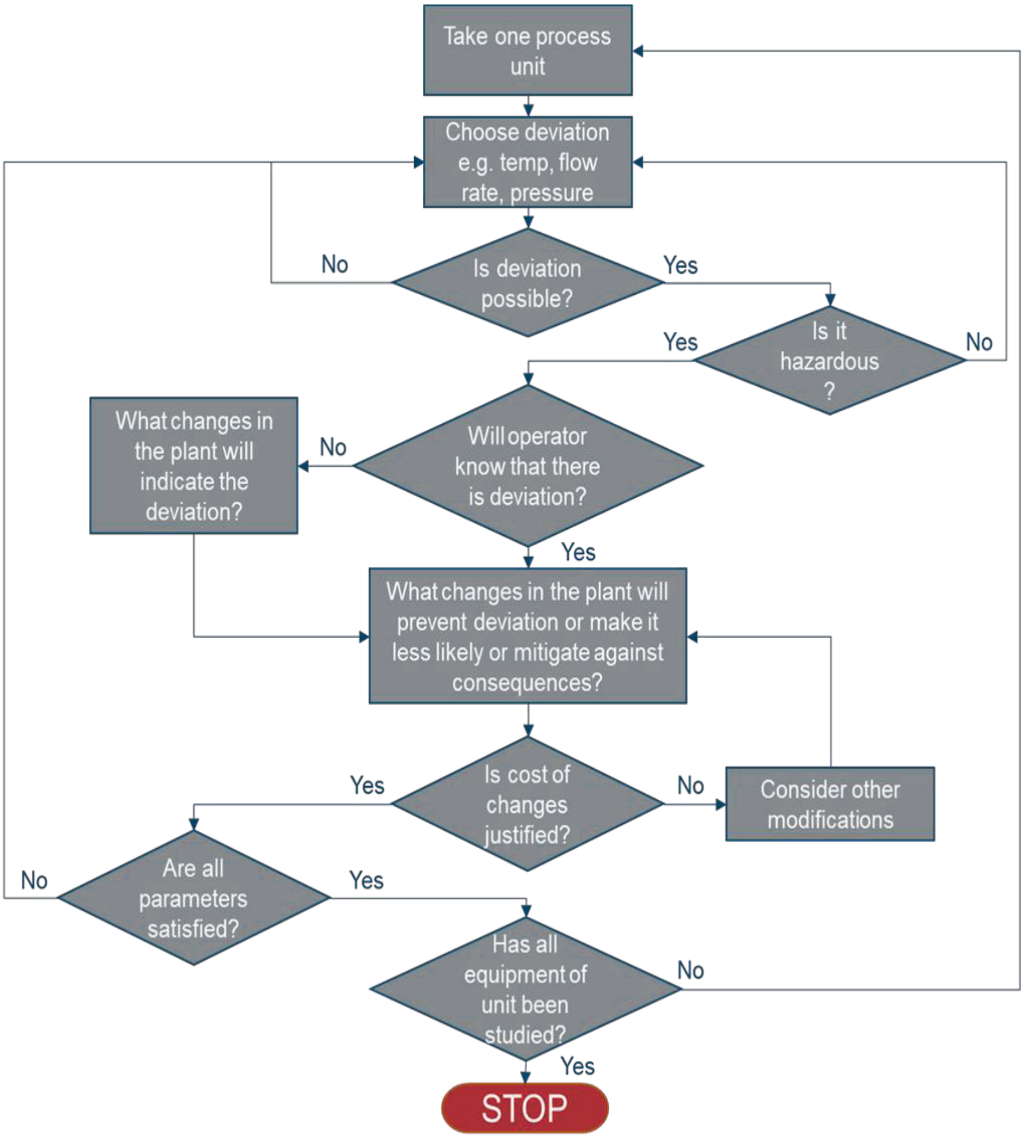
[43] P. K. Marhavilas, D. Koulouriotis and V. Gemeni, "Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000–2009", *Journal of Loss Prevention in the Process Industries*, vol. 24, No. 5 (September, 2011), pp. 477–523.

[44] Faisal I. Khan and S. A. Abbasi, "OptHAZOP – an effective and optimum approach for HAZOP study", *Journal of Loss Prevention in the Process Industries*, vol. 10, No. 3 (May 1997), pp. 191–204.

Guide Word	*Meaning*	*Parameter*	*Deviation*
Part of	Qualitative decrease	Concentration Flow Level	Concentration decrease Flow decrease Level decrease
As-Well-As	Qualitative increase	Concentration of impurity Temperature of substance Level of impurity Pressure of substance Flow of impurity	Concentration increase Temperature increase Level increase Pressure increase Flow increases
Other than	Complete substitution	Concentration of desired substance Level of desired substance Flow of desired substance	Concentration zero Level zero Flow rate zero

Source: Faisal I. Khan and S. A. Abbasi, "Techniques and methodologies for risk analysis in chemical process industries", *Journal of Loss Prevention in the Process Industries,* Volume 11, Number 4 (July 1998), 266.

Figure 3.
Hazard and Operability process stream



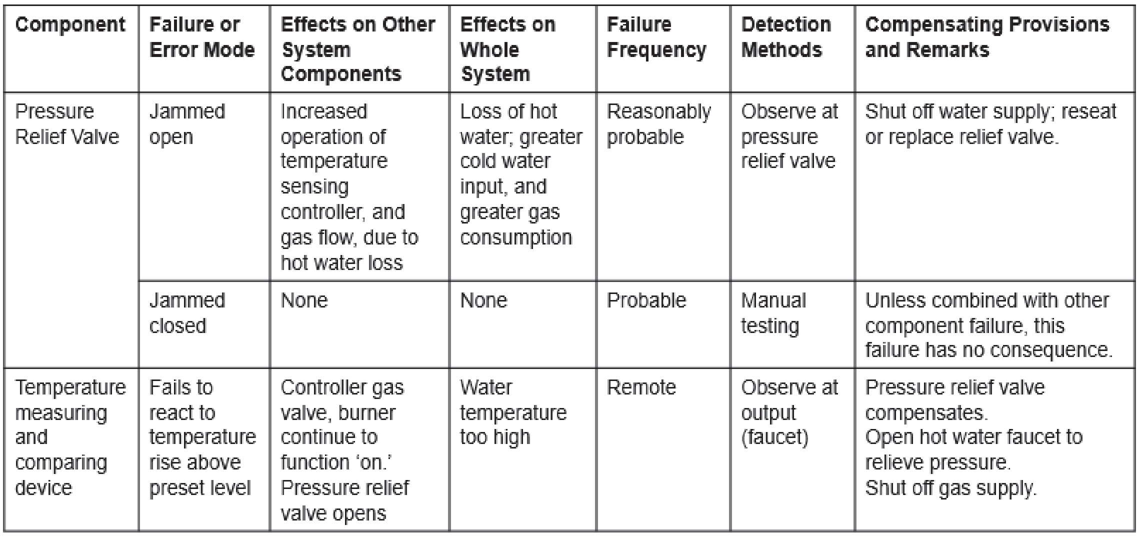
Source: Adapted from Faisal I. Khan and S. A. Abbasi, "OptHAZOP – an effective and optimum approach for HAZOP study", *Journal of Loss Prevention in the Process Industries*, Volume 10, Number 3 (May 1997) 192.

The HazOp team uses this systematic framework to determine appropriate measures to reduce the consequence and/or frequency of a deviation. This method also allows for simultaneous evaluation of the causes and consequences of a deviation and applies to any system or procedure.[45] HazOps are generally time-consuming and require a multidisciplinary team to execute.

3.3. Failure modes and effects analysis

Failure modes and effects analysis (FMEA) is an inductive, bottom-up method that compiles the failure modes of selected equipment and the consequences associated with the failure. The failure mode describes how a component of a system fails (open, closed, etc.) and the effect is determined by the system's response to the failure.[46] An example FMEA worksheet is provided in table 4.

Table 4.
Failure modes and effects analysis: example result for a process plant



Component	Failure or Error Mode	Effects on Other System Components	Effects on Whole System	Failure Frequency	Detection Methods	Compensating Provisions and Remarks
Pressure Relief Valve	Jammed open	Increased operation of temperature sensing controller, and gas flow, due to hot water loss	Loss of hot water; greater cold water input, and greater gas consumption	Reasonably probable	Observe at pressure relief valve	Shut off water supply; reseat or replace relief valve.
	Jammed closed	None	None	Probable	Manual testing	Unless combined with other component failure, this failure has no consequence.
Temperature measuring and comparing device	Fails to react to temperature rise above preset level	Controller gas valve, burner continue to function 'on.' Pressure relief valve opens	Water temperature too high	Remote	Observe at output (faucet)	Pressure relief valve compensates. Open hot water faucet to relieve pressure. Shut off gas supply.

Source: Adapted from Sam Mannan (ed.), *Lees' Loss Prevention in the Process Industries* (4th edition, Elsevier 2012) 255; and J.L. Recht, Systems safety analysis: Failure mode and effect (National Safety News February, 1966) 24; and D.M. Himmelblau, *Fault Detection and Diagnosis in Chemical and Petrochemical Processes* (Elsevier Amsterdam, 1978).

FMEA can be effective due to its systematic and structured approach; however, failure modes of new systems may not be known from practice and the framework could make it difficult to focus on critical failures. FMEA can be extended to FMECA by including the criticality of failure mode, which provides a more quantitative basis for analysing risks.[47]

3.4. Hazard and Operability with risk tiers

The HazOp method can be extended to include a risk analysis component; by using a risk matrix, the team can illustrate that the developed recommendations adequately reduce identified risks. The HazOp worksheet can be expanded to include baseline risk for each scenario, risk with existing safeguards, and risk after implementing additional safeguards.

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[45] Mannan, *Lees' Loss*.

[46] CCPS, *Guidelines for Hazard*; and J. F. W. Peeters, R.J.I. Basten and T. Tinga, "Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner", *Reliability Engineering and System Safety*, vol. 172 (April 2017).

[47] Mannan, *Lees' Loss*.

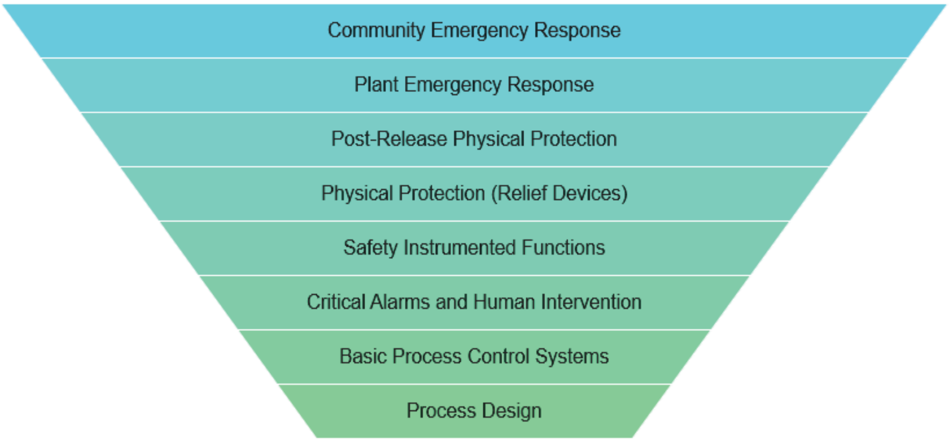
A risk matrix could be used with severity and frequency tiers to inform the HazOp team during the risk analysis exercise (see section 3.2). Although risk levels are determined by consensus, selection of consequence severity and probability is often limited to the biases and experiences of those in the workshop; applying quantitative assessment can provide more objective, defensible values.

3.5. Layers of Protection Analysis

LOPA is a simplified form of quantitative risk analysis. It uses order of magnitude categories for initiating cause frequency, consequence severity and likelihood of failure of safeguards — hence it is considered a semi-quantitative risk analysis tool.[48] Safeguards analysed in LOPA are defined as independent protection layers. Figure 4 depicts independent protection layers that may be in place to protect against a hazard.

Figure 4.

Independent protection layers against a possible accident



Source: Center for Chemical Process Safety, Layer of Protection Analysis: Simplified Process Risk Assessment (American Institute of Chemical Engineers, 2001), 12.

LOPA is a scenario-based risk analysis method following the steps below:

(a) Identify a target consequence, determine possible scenarios, and select an incident scenario;

(b) Identify the cause of the selected scenario and determine its frequency;

(c) Define the independent protection layers and estimate their failure frequencies;

(d) Calculate the overall frequency of the scenario by combining cause and independent protection layer failures;

(e) Determine risk level for the scenario by identifying magnitude of the consequence and continue with risk evaluation.

LOPA requires less time and effort than a fully quantitative method, facilitates the determination of more precise cause-consequence pairs, and can help resolve conflicts in decision-making by providing a consistent framework for risk analysis.[49] LOPA itself does not systematically identify hazards and must be based on a hazard analysis tool such as a HazOp or FMEA.[50]

3.6. Consequence analysis (release models and effect models)

Once a source term is established, release models are developed to define time-dependent characteristics of the scenario. For liquid releases, key characteristics are flow rates, evaporation rates, and pool spill size; for gas or vapor discharges, total anticipated volume of release and release rates are needed. These characteristics provide the means to calculate consequences (e.g., the size of a

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[48] CCPS, *Guidelines for Hazard*.

[49] CCPS, *Guidelines for Hazard*.

[50] Ibid.

vapour cloud is needed to estimate the fireball size and pressure wave resulting from an explosion). Specific to gas or vapor releases, dispersion models are used to provide an estimate of the area affected and average vapor concentrations expected. To develop the models, the release rate of the gas, height of release, atmospheric conditions, geometry, temperature, pressure and release diameter are required. In addition, the density of the gas or vapour, as well as the release type, is considered (instantaneous, continuous or varying with time). Software tools used to estimate the areas affected from a source term are listed in the annex to Part 2.

For the selected scenario, the applicable events could be further studied using effect models where the objective is to determine the effects of toxic material exposure, thermal effects from fire, or pressure/flame effects from an explosion. For explosions and fire, effects could be overpressure and radiant heat flux causing injuries or fatalities; for toxic releases, effects could include threshold exposure limits (such as immediately dangerous to life or health). Based on these effect models, lethal distances can be calculated to determine the potential number of fatalities or injuries based on the population density. Analysis could be extended to study environmental consequences further away from the source, such as determining concentrations of toxic chemical exposure to people in off-site targets (e.g., residential or commercial areas), or quantifying chemical releases into soils or waterways.

3.7. Fault Tree Analysis

FTA is a deductive method to determine the occurrence of an upset condition or loss of containment event. The top event of the tree is defined as the event to be studied, and the tree is built by developing a list of contributing factors that could lead to the top event individually or in combination (denoted through "and"/"or" gates).[51] These contributing factors are further broken down into basic events and the fault tree can determine the minimum "cut sets," i.e., the minimum sets of component (and human) failures that, if they occur, lead to the top event (see figure 5 for example of fault tree).

FTA allows the analysis team to determine possible causes of an event deductively, and critical failure scenarios. The FTA structure helps to visualize the hazard and allows the team to concentrate on one scenario or hazard at a time in detail.[52] When combined with failure frequencies, the fault tree provides quantitative failure rate information to identify the chains of events that pose the highest risks and so identify where prevention and/or mitigation should be focused. If there is an "and" linkage in the fault tree, the failure probabilities for the next higher event are multiplied. If there is an "or" linkage, the failure probabilities are added. Frequencies can also be calculated. The fault tree method also provides the ability to: consider and account for the effectiveness of preventative measures;[53] and account for "failure on demand" (the probability that a safety system will not be able to perform its safety function when called upon).

FTA can be complex, requiring a thorough understanding of the system being studied. However, it is widely used as a fundamental method to assess event frequencies for quantitative risk analysis.

A weakness of FTA is that failure frequency and on-demand probability data for system components and events can have associated uncertainty, and may not be readily available, particularly if the system or component is new and lacks an established operational history. In such cases, these data may need to be estimated through engineering judgement or using ranges with a sensitivity analysis rather than relying on well-characterized data. To develop a harmonized risk assessment process within a country, it is therefore important that plant owners and authorities together draw up framework reports or principles in which uniform failure probabilities are elaborated.

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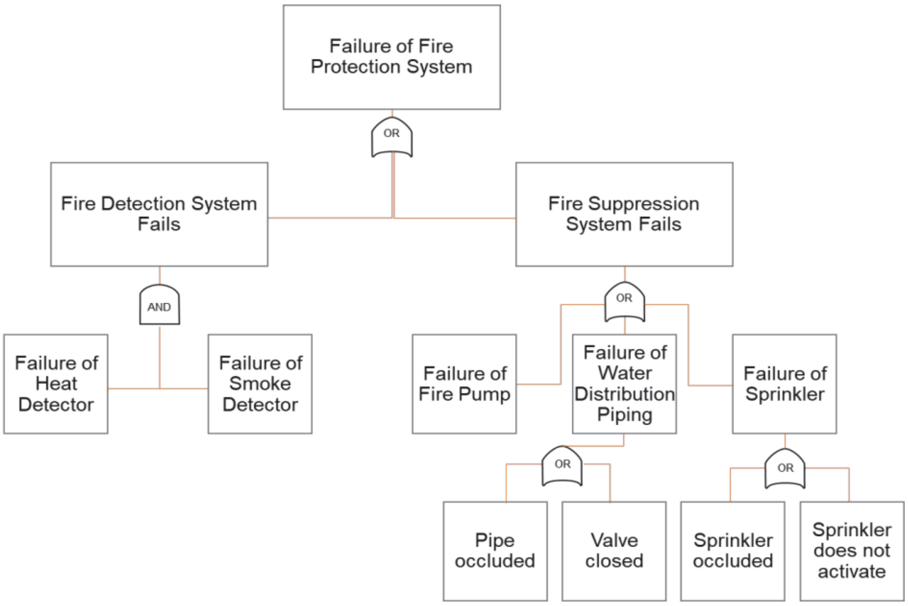
[51] CCPS, *Guidelines for Hazard*.

[52] Khan, "Techniques and Methodologies".

[53] International Electrotechnical Commission (IEC), IEC Standard 61025:2006, "Fault Tree Analysis (FTA)" (December 2006).

Figure 5.
Example fault tree diagram for fire protection system



Source: Created by author of present report.

3.8. Event Tree Analysis

Event Tree Analysis (ETA) is an inductive method to identify various scenarios that could occur once a "top event" has occurred. ETA is a tree that identifies various sequences of events, both failures and successes, that can lead to consequences,[54] given that the initiating event has occurred (see figure 6).

Like FTA, ETA provides a graphical aid to visualize possible outcomes following an initiating event; however, the exercise can be complex and time consuming. The two methods are often linked in that FTA considers the likelihood of the initiating event occurring and ETA considers the likelihood of one or more consequences given that the initiating event occurs. Accordingly, FTA considers and accounts for prevention measures and ETA considers and accounts for mitigation measures. As with FTA, the failure frequencies and likelihood of consequence exposures are sometimes not readily available and need to be estimated to allow quantitative analysis to proceed.

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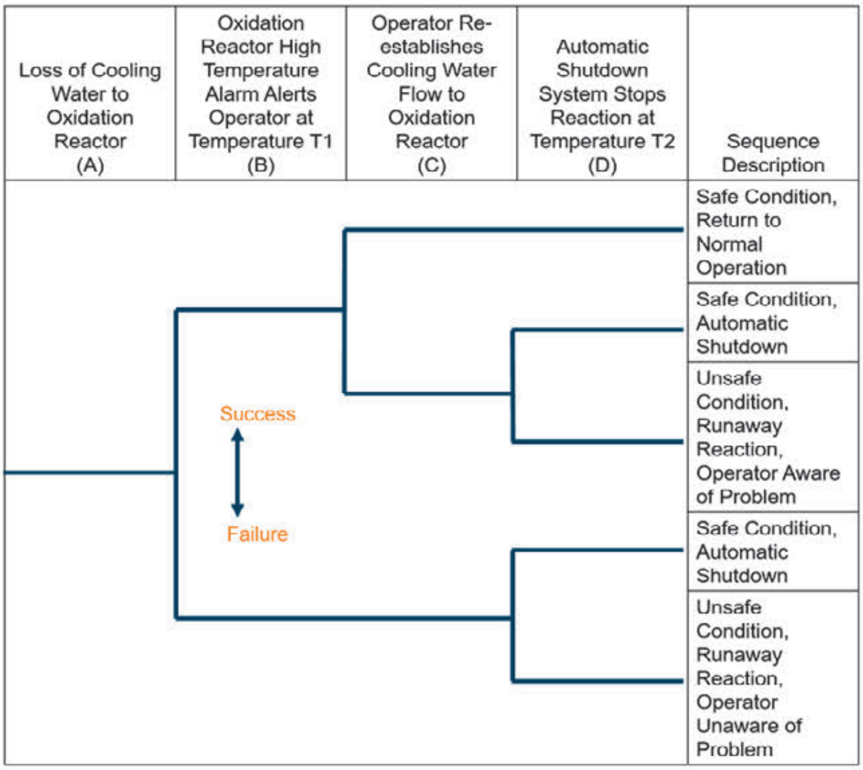
[54] Marhavilas "Risk Analysis".

Figure 6.

Event tree for the example initiating cause "loss of cooling water to the oxidation reactor"



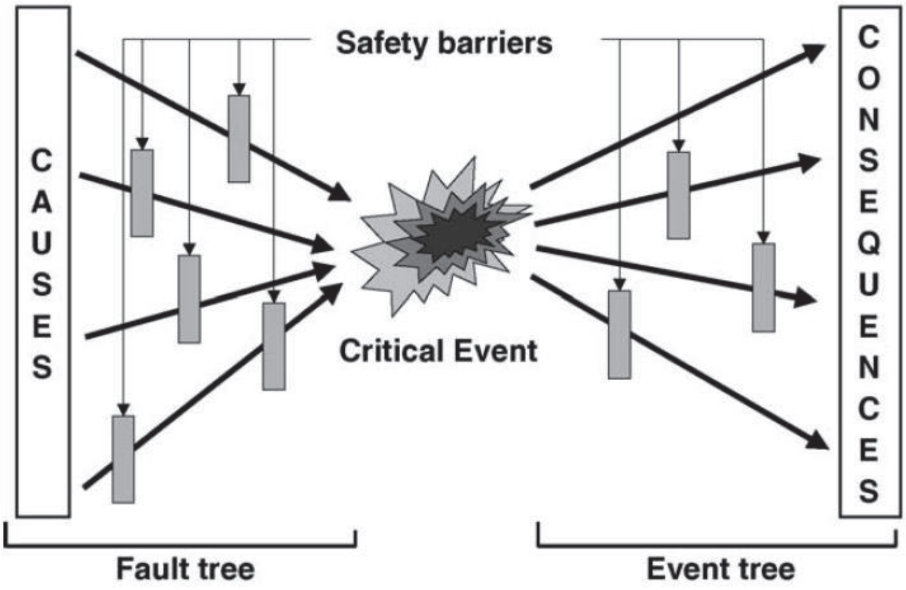
Source: Center for Chemical Process Safety, Guidelines for Hazard Evaluation Procedures: Third Edition (American Institute of Chemical Engineers, 2008), 166.

3.9. Bow-tie model

The bow-tie model (figure 7) is a scenario-based risk analysis tool most often regarded as a combination of FTA and ETA. The loss of containment event (or other initiating event) is placed at the centre, with its causes and consequences respectively on its left- and right-hand sides.

Due to its clear visual and compact construction, the bow-tie model is a powerful tool to represent major hazards of relatively simple facilities (e.g., storage facilities where operations are inherently limited), to communicate and coordinate with stakeholders having less expertise in the field of risk assessment, and provide a clear framework for emergency response planning purposes by showing the different accidental paths from the same loss of containment event and the safety barriers in place to mitigate their effects. Although mostly used as a visual tool, the bow-tie model can be employed as a quantitative risk analysis method through use of fault tree and event tree data, along with probability of occurrence or failure frequencies of the safety barriers, to determine risk associated with a studied event.

Figure 7.
Bow-tie model from ARAMIS project



Source: Valérie de Dianous and Cécile Fiévez, "ARAMIS project: A more explicit demonstration of risk control through the use of bow-tie diagrams and the evaluation of safety barrier performance", *Journal of Hazardous Materials*, Volume 130, Number 3 (March 2006) 221.

4. Important considerations in selecting risk analysis tools

Selection of risk analysis tools is dictated by several factors, including the:

(a) Objectives of the entity undergoing the risk analysis and required level of rigour;

(b) Criteria to be met (e.g., quantitative risk target, risk matrix target);

(c) Knowledge of personnel and documentation available as a basis for the risk analysis;

(d) Complexity of the process;

(e) Relative magnitude of the hazard and potential risk levels;

(f) Stage of project design.

The rigour of the risk analysis method (e.g., qualitative versus quantitative) can be based on the complexity of the process, type of industry, or the country-specific legal requirements. Simple processes and hazards may be adequately covered by a qualitative method, whereas a complex process may need a quantitative method. Table 5 summarizes the advantages and challenges associated with each of the risk analysis methods discussed in this section.

Table 5.
Comparison of risk analysis tools and methods

Method/tool	*Advantages*	*Challenges*	*Applicable risk assessment steps (see figure 2)*
What-if or What-if/checklist	Identifies hazards or specific accident events that could result in undesirable consequences Relatively easy to apply	Determines only hazard consequences Loosely structured tool	Risk identification: Identify hazards and vulnerable targets

Method/tool	*Advantages*	*Challenges*	*Applicable risk assessment steps (see figure 2)*
HazOp	Systematic method to identify and document hazards through imaginative thinking Simultaneous evaluation of causes and consequences of deviations Inherently comprehensive	Does not include risk categorization Time consuming Requires detailed process knowledge; may not be suitable for transboundary applications due to possible trade secrets	Risk dentification: Identify hazards and vulnerable targets
HazOp with risk tiers	Same as HazOp, plus: Applicable to any system or procedure Includes risk categorization to better define hazards and need for risk reduction measures	Time consuming Requires multidisciplinary team to execute Risk selection limited to experience of HazOp team	Risk identification: Identify hazards and vulnerable targets
FMEA/FMECA	Inductive analysis method to identify failure modes by analysing each system component systematically Can be expanded to quantitative method through use of criticality analysis (FMECA)	Failure behaviours of new systems not known from practice May be difficult to focus on most critical failures	Risk analysis: Develop hazardous incidents, mitigating features
LOPA	Requires less time and effort than fully quantitative method Facilitates determination of more precise cause-consequence pairs Provides clear understanding of protection layers	Does not systematically identify hazards Must be based on hazard analysis tool May not be effective for complex scenarios	Risk analysis: Identify mitigating features, estimate frequencies
Consequence analysis	If done adequately, provides high level of confidence in results and robust justification for risk-based decision making	Requires fully quantitative scenario development and effects models Requires verification and validation for confidence in accuracy of results	Risk analysis: Estimate consequences

Method/tool	*Advantages*	*Challenges*	*Applicable risk assessment steps (see figure 2)*
FTA	Identifies and models combinations of equipment failures, human errors, and external conditions leading to accident Allows team to concentrate on one scenario or hazard at a time in detail Deductive modelling method Highly structured method Determines causes in depth Provides graphical aid to visualize system and failure modes	Used most often as system-level method rather than consequence-based Requires frequency of failure data for equipment	Risk analysis: Estimate frequencies
ETA	Highly structured method Determines causes in depth Provides a graphical aid to visualize outcome	Failure frequencies and likelihood of consequence exposures sometimes not readily available May require use of FTA in combination with ETA	Risk analysis: Estimate frequencies
Bow-tie	Visual tool allows for clear understanding of event paths Can be used qualitatively	Requires development of FTA and ETA for thorough understanding	Risk analysis: Identify mitigating features

Sources: Table created by the author of the present report, based on information summarized in CCPS, Guidelines for Hazard; Mannan, Lees' Loss; and Peeters, "Improving failure analysis".

5. Results of risk analysis step

The results of risk analysis are used as a basis for the next step, risk evaluation. Typical risk analysis output includes:

(a) A list of scenarios evaluated, along with causes and consequence targets;

(b) The risk levels as calculated or determined for each scenario (e.g., risk of fatality due to rupture of process vessel from overpressure);

(c) In a transboundary context, appropriate methods for conveying onshore risk include location-specific individual risk, societal risk, or straight consequence contours;

(d) To document environmental impact, a threshold value consequence assessment is appropriate (ecotoxicity concentrations);

(e) Calculated and plotted probability-consequence diagram (f-n curves).

C. Risk evaluation

Risk evaluation is the next step once risk levels for identified scenarios have been determined. This step develops a level or range in which the calculated or determined risk level is acceptable to stakeholders.

1. Risk acceptance criteria

To determine whether a studied loss event or scenario is acceptable to stakeholders without further safety measures, an acceptable risk level or range must be established. This "tolerable" risk should be defined beforehand as part of developing the risk assessment framework and agreed upon by stakeholders or prescribed in a legal framework by the authorities. These criteria may vary based on the population affected (e.g., on-site, off-site, sensitive receptors, environmental protection targets such as surface water and groundwater, etc.) and the risk aversion of the community. It is important to note that risk acceptability has cultural, geographical, and political elements that may result in differing risk acceptance criteria amongst a group of countries or stakeholders. Risk acceptance criteria should be developed and applied in alignment with risk analysis methodology and per stakeholder requirements:

(a) Qualitative: Risk tiers such as high/medium/low;

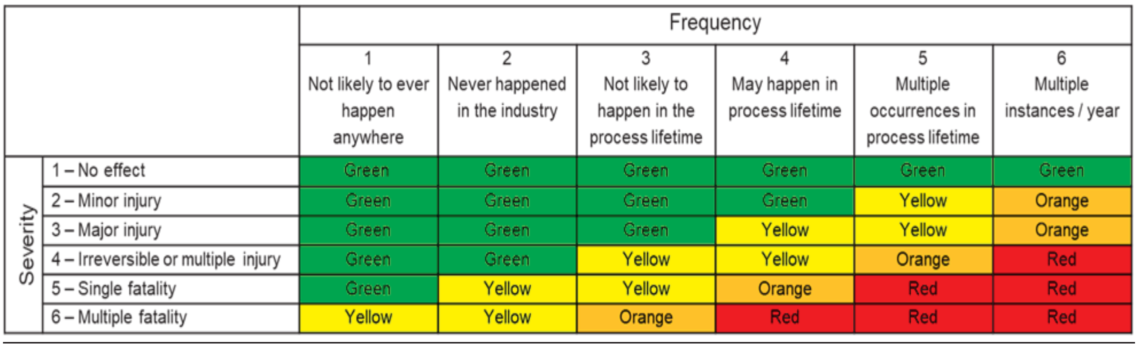
(b) Semi-quantitative: Numbered risk tiers;

(c) Quantitative: Numerical risk targets.

1.1. Qualitative or semi-quantitative risk criteria

A risk matrix is a typical tool developed by stakeholders to qualitatively represent a tiered risk profile. Typically, the severity element is focused on personnel exposure (e.g., injury, disability, fatality), but other factors such as property damage, environmental impacts, business interruption and reputational impacts could be considered. Table 6 illustrates a sample risk matrix and description of tiers.

Table 6.
Sample risk matrix



		Frequency					
		1 Not likely to ever happen anywhere	2 Never happened in the industry	3 Not likely to happen in the process lifetime	4 May happen in process lifetime	5 Multiple occurrences in process lifetime	6 Multiple instances / year
Severity	1 – No effect	Green	Green	Green	Green	Green	Green
	2 – Minor injury	Green	Green	Green	Green	Yellow	Orange
	3 – Major injury	Green	Green	Green	Yellow	Yellow	Orange
	4 – Irreversible or multiple injury	Green	Green	Yellow	Yellow	Orange	Red
	5 – Single fatality	Green	Yellow	Yellow	Orange	Red	Red
	6 – Multiple fatality	Yellow	Yellow	Orange	Red	Red	Red

Source: Created by author of present report.

Risk categories are predetermined based on stakeholder input, and scenarios resulting in higher risk levels will necessitate action for risk reduction. In table 6, the green risk level would generally represent an acceptable risk requiring no further action, the yellow risk level a tolerable risk level requiring consideration of recommended actions, and the red and orange risk levels an intolerable/ unacceptable level of risk requiring further action for risk reduction.

1.2. Individual risk criteria

Risk criteria for quantitative risk analysis should be categorized by quantifiable level. When considering possible effects to an individual person in the context of a consequence involving an industrial hazard, individual risk criteria are used.

It is challenging to obtain consensus on what constitutes "acceptable risk" across stakeholders, especially in a transboundary context. There can be differences of several orders of magnitude when considering what is acceptable or unacceptable risk (see figure 8). Thus, subsequent refinements are prudent in gaining alignment among stakeholders.[55]

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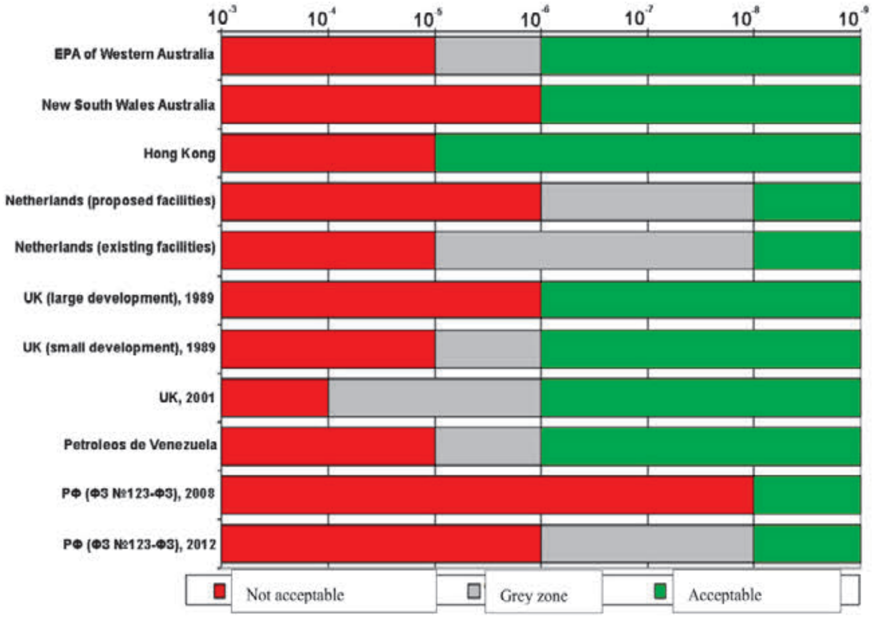
[55] Summary report of the UNECE Seminar on Risk Assessment Methodologies (2018), available at https://unece.org/fileadmin/DAM/env/documents/2018/TEIA/Report_of_the_UNECE_risk_assessment_seminar_4_December_2018.pdf.

Figure 8.
Comparison of countries' individual risk acceptance criteria (probability of individual exposure to a fatal hazard in one year)



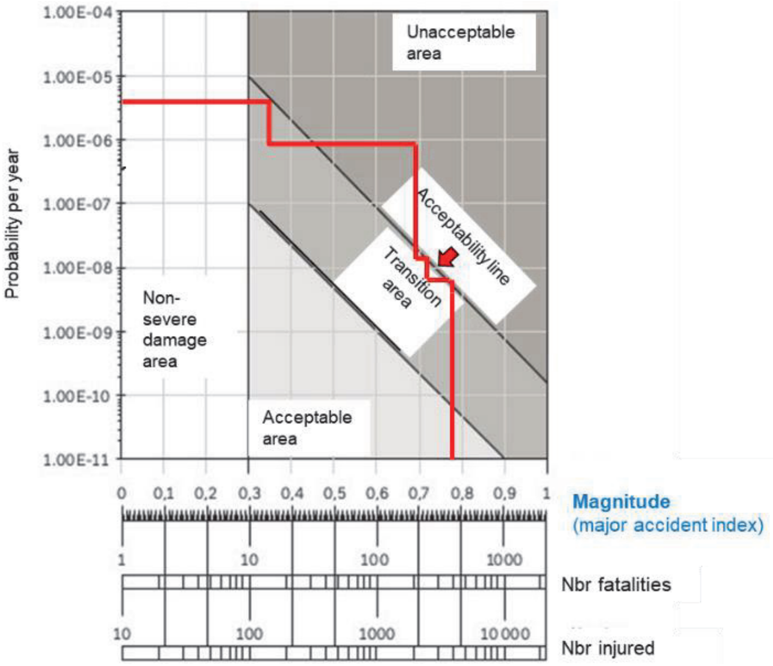
Source: Mikhail Lisanov, "Methodological framework for risk assessment in the Russian Federation", presentation, UNECE seminar on risk assessment methodologies (Geneva, 4 December 2018).

Abbreviations: EPA, Environmental Protection Agency; Hong Kong, Hong Kong, China; UK, United Kingdom.

1.3. Societal risk criteria

Societal risk criteria are used in risk evaluations when considering the risks presented to multiple people or a population (see figure 9).

Figure 9.
Evaluation criteria from Switzerland based on f-n curves



Source: M. Merkofer et. al, Beurteilungskriterien zur Störfallverordnung, Federal Office for the Environment, Switzerland, 2018

Abbreviations: Nbr, number.

2. As Low as Reasonably Practicable/Achievable

The "As Low as Reasonably Practicable/Achievable" (ALARP/ALARA) concept, predominant in the United States of America and the United Kingdom of Great Britain and Northern Ireland, addresses situations where the amount of risk remaining after risk controls have been applied is not clearly in the "acceptable" nor "intolerable" range. Recognizing that it is impractical to reduce risk to zero at exorbitant cost, the ALARP/ALARA principle allows users to weigh risk reduction against societal benefit. For a risk to be ALARP/ALARA, the user must demonstrate that costs associated with further risk reduction are "grossly disproportionate" to the benefit gained. [56] The terms "reasonably practicable" and "grossly disproportionate" are legally relevant; the exhaustive interpretation of these terms is beyond the scope of this document.

3. Cost-benefit analysis

A cost-benefit analysis is a systematic method for estimating strengths and weaknesses of possible risk reduction measures in consideration of economic cost. Risk curves with and without additional safety measures are determined; the costs associated with these safety measures are calculated and compared to the monetized risk benefit.

Within the context of risk assessment for chemical facilities, a key benefit of cost-benefit analysis is deciding among several safety options that achieve comparable risk reductions. Numerous methods are available, including qualitative "risk points" achieved, minimum dollars to reach "acceptable risk" or "gross disproportionality" to the risk reduction.

A numeric cost-benefit analysis in a risk assessment context can be challenging to obtain given the complexity of safety systems and associated life cycle costs including maintenance, inspection, and downtime. Specifically, safety instrumented systems (SIS) implementations tend to have very high operational costs, from maintenance and testing and also due to interference and spurious action that can be challenging to quantify. Thus, an evaluation in terms of orders of magnitude is generally recommended when comparing safety options. Other considerations (e.g., ease of implementation) can also be included.

There are substantial challenges with applying cost-benefit analysis in the context of human safety, not least of which are the political and social consequences of assigning a monetary value to human life, and use of historical events as a basis for cost rather than the worst possible accident. Certain stakeholders may also discount or be unaware of safety features that provide most of the risk reduction, already implemented and accounted for prior to the cost-benefit study. Consequently, the use of cost-benefit analysis for risk reduction is generally limited, focusing on environmental (and other non-human) risks. Examples include:

(a) The United Kingdom of Great Britain and Northern Ireland, which applies cost-benefit analysis in determining ALARP (see section C.2) based on a court decision of how much a company should be willing to spend to save a life;[57]

(b) Switzerland, which applies cost-benefit analysis for environmental risks.[58]

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[56] CCPS, *Guidelines for Developing Quantitative*.

[57] Health and Safety Executive, "Appraisal values or 'unit costs''", available at www.hse.gov.uk/economics/eauappraisal.htm.

[58] M. Merkofer et al., Beurteilungskriterien zur Störfallverordnung, (Bern, Federal Office for the Enivronment, 2018).

V. Benefits and challenges of risk assessments

A. Benefits of risk assessment and applying risk assessment methodology

1. Transboundary considerations

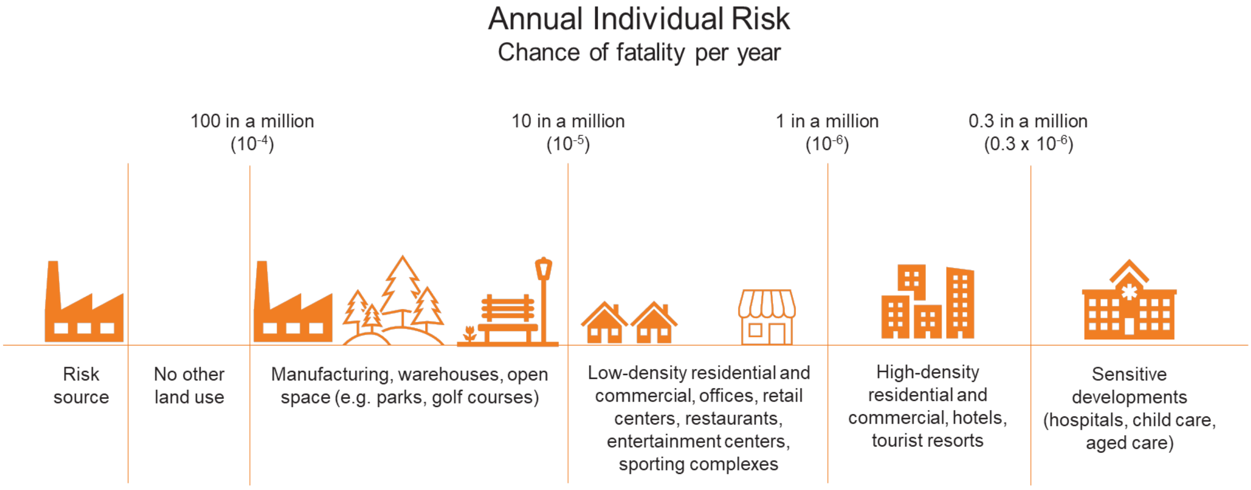
When applied in a transboundary context and properly communicated, risk assessments can facilitate improved information-sharing, understanding of different methods used, enhanced management of joint risks, and better prevention, preparedness, and response to industrial accidents.

2. Land-use planning, population/worker protection

One of the priorities of chemical facilities is to contain major accident hazards within their property boundaries, but this is not always possible when large quantities of hazardous substances are involved or when space is limited. Thus, quantitative risk analysis is indispensable for land-use planning and population protection, both within and across national borders.

Risk assessments can support land-use planning by overlaying broad order-of-magnitude risk contours onto land-use type (see figure 10). Industry guidance is available for this specific application through several organizations.[59] By comparing outputs from risk assessments to characteristics of potential future uses of adjacent space, critical exposures can be avoided. One example compares a toxic release map against land uses with high densities of public outdoor use.

Figure 10.
Allowable land and uses



Sources: Major Industrial Accidents Council of Canada (MIACC), Risk-based Land-use Planning Guidelines (Ottawa, 1995)

Policymakers should take appropriate measures to mitigate existing risks for the population and the environment, considering information from the risk assessment and other sources such as environmental impact assessments. More information about a coherent, integrated approach to environmental and risk assessment is available in the Guidance on Land-Use Planning,[60] in line with Parties' obligations under the Convention on Environmental Impact Assessment in a Transboundary Context, its Protocol on Strategic Environmental Assessment and the Industrial Accidents Convention.

3. Emergency preparedness

Advance awareness of potential off-site consequences allows emergency responders to pre-plan for critical activities including securing site boundaries, notifying the public to shelter-in-place, preparing

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[59] Major Industrial Accidents Council of Canada (MIACC), *Risk-based Land-use Planning Guidelines* (Ottawa, 1995).

[60] *Guidance on Land-use Planning, the Siting of Hazardous Activities and Related Safety Aspects*" (United Nations publication, Sales No. E.18.II.E.6).

health-care providers for specific treatment protocols, and establishing surge capacity for emergency response. This concept has been a focus of the Inter-Agency Coordination Group on Industrial and Chemical Accidents.[61]

4. Communication and coordination among stakeholders and across country borders

Risk assessment is conducted through multidisciplinary teamwork. Brainstorming sessions foster participation and further enhance communication and coordination among stakeholders (operators, workers, other facility personnel, off-site population, regulators, interest groups, local and neighbouring enforcing authorities) and beyond country borders. Stakeholder communication in this framework can lead to better risk awareness, executive management support, collaborative decisions, and less risk aversion among the community.

5. Harmonized methods for risk ranking and control

Applying comprehensive, systemic, well-described, standardized risk assessment methods enables objective evaluations and leads to more consistent decisions to manage risks. Major scenarios can be ranked and main risk drivers identified so that appropriate risk reduction measures are taken to lower the global risk level of a facility in the most efficient way. Accurately estimating the likelihood of scenarios leading to a catastrophic event identifies main risk drivers and enables allocation of resources to lower the likelihood of these leading contributors and the overall event.[62] Uniform risk assessment criteria help to ensure an equal and high level of protection for the population and the environment. Periodic revalidation of risk assessments can contribute to a continuous improvement loop.

6. Demonstration of defence in depth

The concept of defence in depth as applied to the chemical industry is referred to as the “layers of protection concept" (see section B.3.5) and creates multiple independent and redundant layers of defence to prevent and mitigate accidents with major consequences. Risk analysis methods allow systemic and detailed investigation of process deviations and enable the creation of multiple layers of protection (including visualization of those layers, e.g., in bow-tie model).

B. Challenges of risk assessment and applying risk assessment methodology

1. Inherent limitations of risk analysis methods

Some risk analysis methods may: be simplified representations of an accident sequence; contain fewer details; and fail to identify all potential causes or consequences for a given scenario (e.g., domino effects). These limitations and challenges are listed below:

(a) Scenario and parameter selection: Describing or selecting scenarios may differ based on the risk management team's judgement/experience, creating a non-uniform approach. Similarly, parameter selection (e.g., duration of an event) can change the outcome of the risk analysis and is often based on judgement;

(b) Number of scenarios: A risk analysis is based on a small set of scenarios (or sometimes a single scenario). If a catastrophic event occurs at a facility, it may differ from that analysed and may require a different response approach from that established. Consequences may therefore be underestimated or not accurately represented;

(c) Data requirements: Often, many input parameters and variables are needed to execute a risk analysis, particularly those that are quantitative. Accurate, representative data are not always readily available to stakeholders. Estimates used in place of accurate data may be subject to uncertainty;

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[61] Organisation for Economic Co-operation and Development, “International efforts for industrial and chemical accidents prevention, preparedness and response", brochure (n.p., n.d.).

[62] Jérôme Taveau and Jensen Hughes, “Fire safety engineering — Fire risk assessment — Part 3: Example of an industrial property." ISO/TR 16732-3. 2013. ISO, Geneva.

(d) Inherent uncertainty: Variables used in risk analysis are not precise, weather conditions at the exact time of an accident are unpredictable, and the condition of terrain, process and storage may differ from when the risk analysis was originally conducted.[63] These variations lead to inherent uncertainty in the analysis;

(e) Non-universality: Risk analyses are developed in a way that makes them highly specific to the properties of a single site. Even for sites or facilities that may be very similar, the risk analysis is not universal and should be tailored to each facility and process;

(f) Results: The results of a risk analysis do not represent absolute truths but rather show relative risk based on the selected scenario and conditions. Additionally, there is a tendency to overestimate the reliability and accuracy of the results.

2. Terminology

Common terminology on risk assessment is crucial for stakeholders to comprehend each other in decision-making processes. However, in practice, different practitioners, institutions or countries use different words for the same concepts. Also, these definitions can evolve with time as existing concepts are refined or new concepts are introduced. Establishing common terminology can be challenging; few comprehensive glossaries covering all aspects of risk assessment exist.

3. Education, experience and expertise

Relevant qualifications are necessary to conduct risk assessment for chemical installations, which involve complex systems. The right combination of education, experience and expertise in specific areas such as chemical engineering, process safety and loss prevention is required to understand basic concepts and implement risk assessment methods and mitigation. Assembling a team with the right expertise remains difficult (especially in terms of education) as few universities offer a process safety specialization. Some certification frameworks validating education and experience in the field of process safety and loss prevention have been set up by organizations (e.g., American Institute of Chemical Engineers; Institution of Chemical Engineers) in recent years, but a more global professional certification is still lacking.

4. Frequency databases

Few frequency databases with absolute values that apply to hazardous activities exist, and when available, associated uncertainties are high given the age of available databases and small number of major incidents (from a statistical perspective).

Generic industry databases do not provide many details and few experts are aware of their inherent limitations because data are mostly untraceable (or, determining the origin of these data, if possible, requires significant research efforts). Other databases from other engineering fields, notably for the determination of probability of failure on demand, are difficult to transpose to chemical installations, again due to the variety of equipment, hazardous substances and operating conditions.

Few initiatives to assemble and validate frequency data have been undertaken within the chemical industry due to inherent challenges and the level of effort necessary to develop and update such a database.[64]

5. Quantifying environmental impacts

Evaluation of environmental causes (Natech) and impact of accidents are often disregarded in risk assessments due to the lack of methods and robust physical models publicly available. This exercise remains difficult in practice due to the many variables that would have to be considered. One available tool focused on Natech events is the RAPID-N software developed by the European Commission Joint Research Centre. Developing and disseminating physical models describing water and soil pollution (specifically used for a safety analysis) would help practitioners in this rather difficult exercise.

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[63] Maureen Heraty Wood and Luciano Fabbri, “Challenges and opportunities for assessing global progress in reducing chemical accident risks”, *Progress in Disaster Science*, vol. 4 (December 2019).

[64] J.R. Taylor, *Hazardous Materials Release and Accident Frequencies for Process Plant: Volume II: Process Unit Release Frequencies – Version 1, Issue 7* (Allerød, Denmark, 2006).

6. Limitations in knowledge of and access to software

A variety of software tools for conducting risk assessments and portions thereof are commercially available (see Part 2, annex). Based on observations from the 2018 UNECE seminar on risk assessment methodologies, awareness of these tools is limited. Access to software can be limited as there is typically a high cost in obtaining and renewing licenses. Consequently, facility owners may not use the software best suited to their application or may only purchase and maintain licenses for one tool that may not be applicable to all scenarios to be studied. Additionally, should a facility owner be using software different from that used by the regulatory agency, challenges in communication between operator and inspector or regulator may arise.

7. State-of-the-art technology

The level of technology associated with a process or facility is inherently considered as the starting point in a risk assessment. Countries with a lower baseline level of technology may require additional safety measures to achieve an acceptable risk level, compared to other countries with more advanced technology that incorporates these additional safety measures within their higher baseline.

VI. Conclusions

This report provides a general overview of risk assessment methodology applicable to risks arising from hazardous activities. The primary outcomes of Part 1 are:

(a) Risk assessment is important to inform decision-making on industrial accident prevention and mitigation, by considering results in land-use planning and siting of hazardous activities;

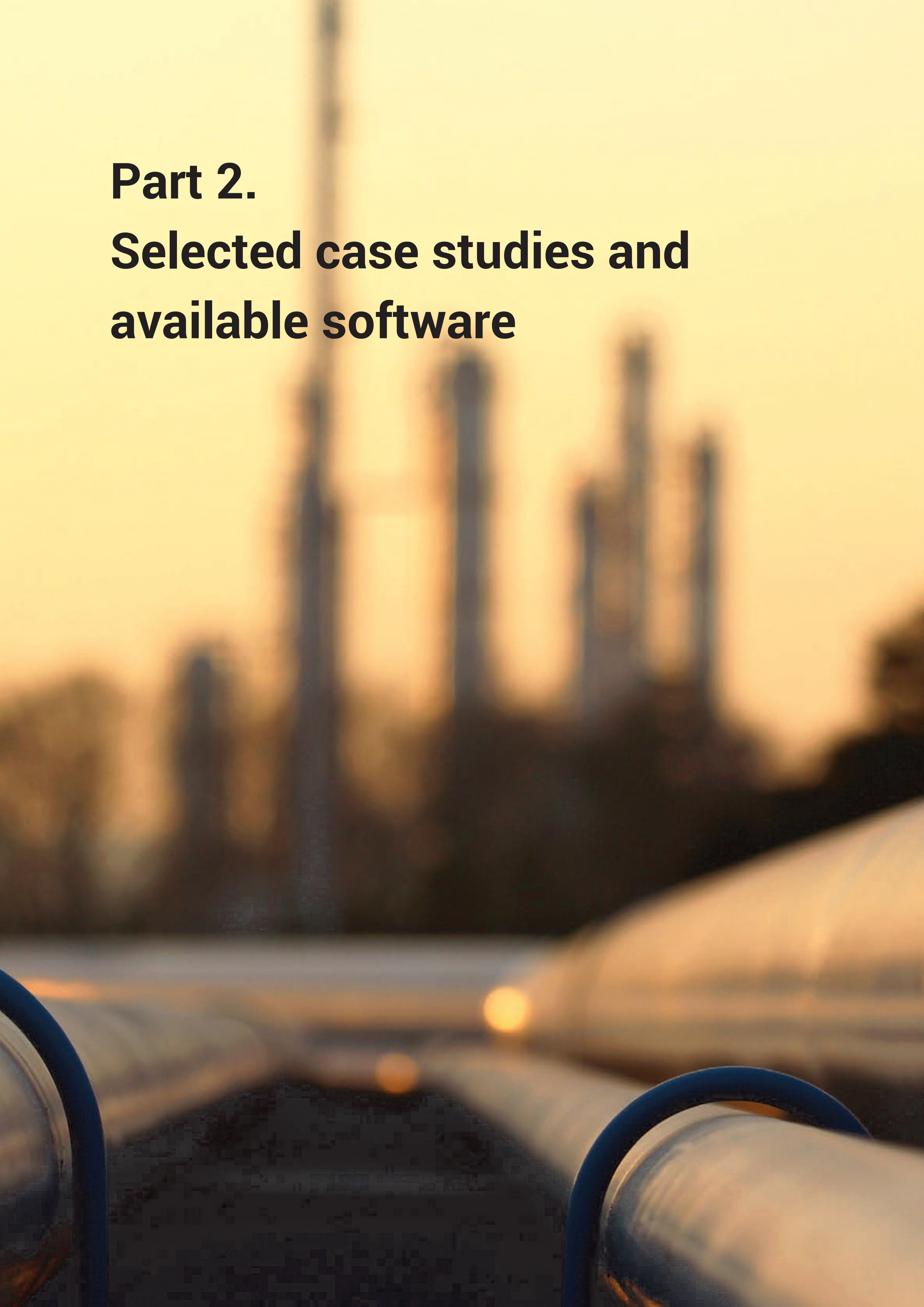
(b) It is essential to share information across neighbouring and riparian countries, and beyond, across the UNECE region, to improve knowledge and understanding of different risk assessment methods, and the use of their results, such as in the process of consultations linked with notification of hazardous activities;

(c) In the longer term, it is important to harmonize definitions of terms commonly used in the risk assessment process (see section B), so that the various stakeholders can have a common understanding despite different backgrounds and roles;

(d) It is important to have a contextual framework for how risk assessment fits into the overall risk management process (see section C and figure 1);

(e) It is crucial to describe the various methods available for conducting risk assessments and when each method is appropriate (see section III), as further subdivided into Risk identification (section A), Risk analysis (section B) and Risk evaluation (Section C).

Part 2 describes case studies where risk assessment methods were applied to UNECE region chemical facilities, including how they apply in a transboundary context. Part 2 (annex) provides additional detail on software tools available to support the various aspects of chemical installation risk assessment.



Part 2.

Selected case studies and available software

I. Introduction and case study selection

This report presents selected case studies where a risk assessment methodology was applied to chemical facilities in the United Nations Economic Commission for Europe (UNECE) region. These case studies span five types of facilities: liquified natural gas (LNG)/liquified petroleum gas (LPG) storage tanks; ammonia refrigeration facilities; oil terminals (hydrocarbon loading/unloading/storage facilities); ammonium nitrate storage facilities; and chlorine facilities. The annex to the present report lists key software tools available to support chemical installation risk assessment.

Several ECE countries were asked to submit case studies on the five above-mentioned types of installations, providing information based on a template. Among the case studies submitted were five transboundary case studies, submitted by three countries; eighteen out of thirty submitted case studies, including three transboundary examples, were selected based on geographic location, facility type and transboundary considerations. Some countries, including those of Eastern Europe, the Caucasus and Central Asia, did not submit case studies due to the sensitive nature of the information requested.

This report is intended to be used in conjunction with the report entitled “Risk assessment for industrial accident prevention: Overview of risk assessment methods” (hereafter called “Part 1”) (ECE/CP.TEIA/2022/8). Part 1 provides a general overview of risk assessment methods applicable to risks arising from hazardous activities.

II. Key information requested

For each case study, a template of requested information was provided, aligned with the following sections for consistency:

(a) Major incident scenarios: A summary (all case studies) of incident scenarios considered in the risk assessment, typically involving loss of containment of the primary hazardous material, and sometimes subsequent reaction or combustion effects;

(b) Release effects and consequence considerations: Discussion (all case studies) of consequences such as fatalities, injuries, environmental effects and off-site damage, including databases and software used for consequence modelling;

(c) Likelihood of occurrence: Discussion (all case studies) of possible incident causes and estimates of incident likelihood, including databases used to determine likelihood of occurrence;

(d) Risk presentation: Evaluation (all case studies) of how incident likelihood and severity were combined and communicated, including degree of analysis (qualitative, semiquantitative or quantitative) and methods for presenting risk scoring criteria;

(e) Risk acceptability criteria: Discussion (all case studies) of risk acceptability criteria used, based on regulations of country/region and stakeholders involved;

(f) Risk reduction measures implemented: In some case studies, further action was taken to reduce risk based on risk assessment results, including through prevention, preparedness, and response measures.

In some case studies, it was unclear whether the stated risk reduction measures were implemented explicitly because of risk assessment findings, or generally as good practices for chemical safety; the former are denoted with the term “additional” risk reduction measures implemented, the latter are denoted with an “*” in the case study summary tables below.

III. Presentation of case studies

A. Liquified natural gas/liquified petroleum gas

1. Finland

The facility is approximately 75,000 m2, located by the sea, within 1 km of a residential area and a wastewater treatment plant and 1.5 km from the closest city (see table 7 for case study summary).

Table 7.
Finland liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Flammable gas/flammable liquid release; LPG gas and liquid release from tanker truck or railway car
Release effects and consequence considerations	No fatalities or injuries of population outside facility would result. No off-site damage or effects on adjacent residential areas are recognized as credible consequences. Only environmental consequences would be vegetation burning near facility. Consequence modelling conducted using Phast software and thermal radiation levels determined to be 3–8 kW/m^2
Likelihood of occurrence	Not assessed; Causes of incident were structural failure, traffic accident or human error
Risk presentation	Risk to people and environment due to incident identified. Qualitative risk assessment conducted using Bow-Tie method. Risk assessment also conducted using quantitative methods such as consequence modelling. Risk matrix not reported
Risk acceptability criteria	None specified
Risk reduction measures implemented*	Gas and fire detectors; SIS such as level control and safety valve; Preventative measures include ATmosphere EXplosible, grounding, regular maintenance, camera monitoring; Protection measures include water-cooling system, extinguishing water system; Internal and external emergency plans and training

Abbreviations: SIS, safety instrumented systems.

2. France

The site is approximately 65,000 m2, surrounded by a canal, roads, factories, and railways (see table 8 for case study summary).

Table 8.
France liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Explosion and fire due to flammable gas/liquid release
Release effects and consequence considerations	Consequence estimated to be 100–1,000 injuries. People in areas surrounding facility may get exposed to overpressure and thermal radiation. IDLH values (inhalation hazard) used to measure consequences and Phast software used for consequence modelling
Likelihood of occurrence	Worst-case scenario deemed “extremely unlikely”. Incident causes include equipment failure, human error and loose connections due to wear and tear. RIVM data used to determine likelihood of incident

Key information	*Description*
Risk presentation	Risk to individuals and surroundings is present. Risk assessment conducted quantitatively using Bow-tie analysis Risk matrix consisted of four qualitative severity levels: moderate (no injury or fatality); serious (minor injury or illness); important (hospitalization due to exposure/permanent disability); catastrophic (fatality) Qualitative levels of likelihood were: extremely unlikely; very unlikely; unlikely; frequent
Risk acceptability criteria	Risk acceptability criteria based on national criteria (Circular of 10 May 2010), using combination of qualitative and quantitative levels. Approaches for assessing human and environmental risks were different. Environmental impacts were considered using case-by-case qualitative approach. Facility management, safety professionals and local competent authority were involved in determining risk matrix and risk acceptance criteria
Risk reduction measures implemented*	Gas and flame detectors; SIS including level control and pressure control; Preventative measures including maintenance, safety valves, training; Protection measures including fire extinguishing systems, water spraying system for cooling down; Emergency response plan

Abbreviations: IDLH, immediately dangerous to life or health; RIVM, National Institute for Public Health and the Environment of the Netherlands.

3. Sweden

The site area is 20,000 m2 and consists of underground LPG storage close to a residential area and a port. The underground LPG storage at the site consists of one pressurized 47,000 m3 cavern and one 100,000 m3 refrigerated cavern (see table 9 for case study summary).

Table 9.
Sweden liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	Toxic gas release resulting in fire and explosion
Release effects and consequence considerations	Up to 50 fatalities expected. Environmental effects include release of LPG into atmosphere. No off-site damage expected. Consequence modelling utilized ALOHA
Likelihood of occurrence	Identified cause for incident was leakage (hose breakage/flange/valve). Likelihood of hose leakage was 3.8×10^{-7}/year. Likelihood of occurrence of incident determined using professional judgement, ETA and databases such as *Classification of Hazardous Locations*[65]

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[65] A. W. Cox, F. P. Lees and M. L. Ang (Warwickshire, Institution of Chemical Engineers, 1990).

Key information	*Description*
Risk presentation	Hazards identified were leakage (hose/flange/valve), fire, BLEVE. Individual and societal risks were investigated Semi-quantitative assessment used primary hazards analysis to determine scenarios, calculating risk using likelihood x consequence, followed by quantitative analysis using ETA for dimensioning scenarios Risk matrix consisted of following risk levels: low (green); middle (yellow); high (red) Likelihood levels were: < once/1000 years; < once/100-1,000 years; < once/10-100 years; < once/1-10 years; < once/year Severity levels were: minor injuries, no need for hospital visit; considerable injuries, need for hospital; serious injuries, permanent harm; significant, fatalities (1); catastrophe, fatalities (>10)
Risk acceptability criteria	In Sweden, no national risk acceptance criteria exist; instead, operators use risk criteria developed from other countries and industry organizations. According to Swedish environmental legislation, operators must prove to authorities and public that they can manage risks and keep them at a low level Operators must take all measures to prevent accident at reasonable cost. It thus becomes a legal matter for authorities and courts to determine what is reasonable cost in relation to risk in each case An individual risk of 10-7 is plotted on a map (see figure 11). Stakeholders involved in risk assessment include safety consultants and company's operating staff
Risk reduction measures implemented*	Gas detectors and alarm systems; Prevention measures including procedures and instructions; Protection measures including emergency stop systems; Emergency response plans for gas release

Abbreviations: ALOHA, Areal Locations of Hazardous Atmospheres; BLEVE, boiling liquid expanding vapour explosion; ETA, event tree analysis.

** A. W. Cox, F. P. Lees and M. L. Ang (Warwickshire, Institution of Chemical Engineers, 1990).*

Figure 11.
Sweden liquified petroleum gas individual risk plot

Sources: Swedish safety report, 14 February 2021, reference MSB 2021-05861, with permission from the Swedish Civil Contingencies Agency

4. Switzerland

The site is approximately 30,000 m2, with a facility area of 1000 m2, consisting of two LPG tanks used to heat railway line switches in winter to prevent freezing. They are close to a residential area, a railway line, an industrial area and a hospital (see table 10 for case study summary).

Table 10.
Switzerland liquified natural gas/liquified petroleum gas case study summary

Key information	*Description*
Major incident scenarios	VCE and BLEVE due to flammable gas/liquid release
Release effects and consequence considerations	Consequences of release include exposure to heat radiation. Transboundary effects were not credible in incident scenario. Risk analysis stated that VCE and BLEVE would result, respectively, in 430 fatalities and 280 fatalities. No environmental effects determined in risk analysis as products of LPG combustion are not ecotoxic. Consequence modelling conducted using EFFECTS. Probit functions used for heat radiation in EFFECTS. Different radii were defined for lethality percentage, e.g., 160 m for 100 per cent lethality (green circle), 310 m for 50 per cent lethality (blue circle) and 450 m for 1 per cent lethality (red circle) (see figures 12 and 13)
Likelihood of occurrence	Initiating events included crash of small aircraft or road vehicle mechanical impact; Likelihood was dependent on fault tree and ETA. Internal Swiss guideline for risk analysis of LPG storage tanks was used. Likelihood of VCE was 10^{-11} and of BLEVE was 10^{-8}
Risk presentation	Main hazard assessed was heat radiation. Risk was presented as societal risk. Risk assessment conducted was quantitative using fault tree and event tree methods. Risk matrix consisted of three different risk levels ranging from acceptable to not acceptable (see figure 14)
Risk acceptability criteria	Risk acceptability criteria were based on guidelines for chemical installations under scope of Manual on the Major Accidents Ordinance.[66] These guidelines were accepted by all stakeholders and are harmonized in Switzerland. Risk acceptability criteria (see figure 15) were summarized using risk sum curve for LPG gas tanks. Relevant stakeholders are federal and cantonal authorities and representatives of different industrial associations
Additional risk reduction measures implemented	Analysed risk was judged to be unacceptable. The two LPG tanks were therefore dismantled and heating carried out using small underground pipes with much lower risk potential

Abbreviations: VCE, vapour cloud explosion.

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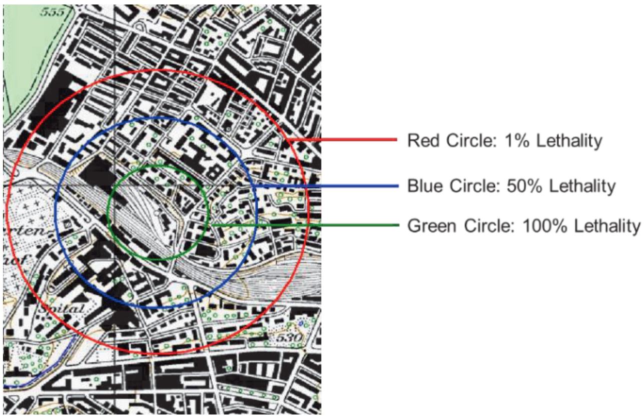
[66] Available at www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/beurteilungskriterien-zur-stoerfallverordnung-stfv.html (French, German and Italian only).

Figure 12.
Switzerland liquified petroleum gas tank

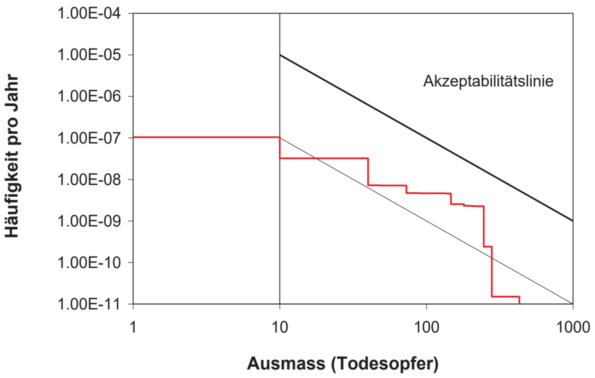
Sources: M. Merkofer, Federal Office for the Environment, Switzerland, 2010.

Figure 13.
Switzerland liquified petroleum gas risk contours



Sources: M. Merkofer, Federal Office for the Environment, Switzerland, 2010.

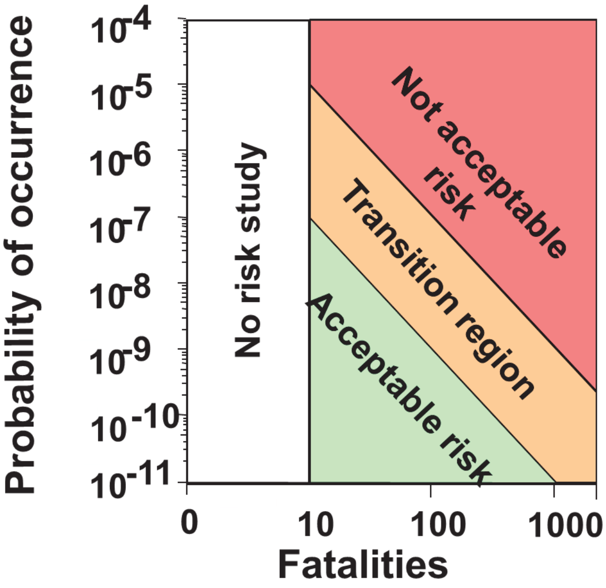
Figure 14.
Switzerland liquified petroleum gas risk presentation



Sources: M. Merkofer, Federal Office for the Environment, Switzerland, 2010.

Note: Vertical axis title reads “Frequency per year”; horizontal axis title reads “Extent (fatalities)”; text inside graph reads “Line of acceptability”.

Figure 15.
Switzerland liquified petroleum gas risk acceptance criteria



Sources: M. Merkofer et al., Evaluation criteria, Federal Office for the Environment, Switzerland, 2018 https://www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/beurteilungskriterien-zur-stoerfallverordnung-stfv.html

Note: White and green level: “Acceptable risk”. Orange level: “Transition region” acceptable after weight of interests. Red level: “Not acceptable risk”.

B.Ammonia refrigeration

1. Estonia

The site is approximately 60,500 m2, located in a port close to residential and sea areas (see table 11 for case study summary).

Table 11.
Estonia ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Ammonia gas release results in a toxic cloud and can cause fire and BLEVE
Release effects and consequence considerations	Consequence of worst-case scenario can affect 2,945 people in danger, of whom 30 per cent directly at risk. Surrounding residential and port areas would require evacuation due to toxic release Three types of zones used for measuring consequence include: IDLH, AEGL-3 (30 min), Lethal Concentration (LC_{50} at 30 minutes) ALOHA was used for consequence modelling
Likelihood of occurrence	Initiating events included human error, technological problems, or thunderstorms. The RIVM Purple Book[67] and Potential Problem Analysis were databases and references used for determining likelihood of incident. Likelihood is less than once every 50 years

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[67] P.A.M. Uijt de Haag and B.J.M. Ale, CPR 18E — Guidelines for quantitative risk assessment: “Purple Book” — Part one: Establishments (n.p., Committee for the Prevention of Disasters (CPR), 1999). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS3.html.

Key information	*Description*
Risk presentation	Individual and societal risk (people, surroundings, environment) and property loss are the different types of risks. Semi-quantitative methods were used for risk assessment. Qualitative methods used for risk assessment included Potential Problem Analysis, methods from RIVM and Purple Book Guidelines for quantitative risk assessment Quantitative methods were used for consequence modelling. Risk matrix was used for risk assessment Severity levels in risk matrix are: little importance; light; hard; very hard; catastrophic Likelihood levels in risk matrix are: very small; small; middle; big; very big
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Risk reduction measures included toxic concentration detection alarms, leak and level alarms, onsite and off-site alarm systems; SIS including level control; Prevention measures including fencing, different alarms, maintenance, exercises/drills; Protection measures including personal protective equipment, water curtain to limit cloud of leaking gas, fire extinguishers; External and internal emergency response plans

Abbreviations: AEGL, Acute Exposure Guideline Level.

2. Finland

The site is approximately 1,300,000 m2, located 2.7 km from the closest city and 1.7 km from the closest residence (see table 12 for case study summary).

Table 12.
Finland ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Toxic ammonia leak from train car from unpressurised tank or pressurised tank
Release effects and consequence considerations	Number of fatalities or injuries not assessed. Worst-case scenario consisted of leakage of 5,000-ton tank resulting in AEGL-3 concentrations at nearest buildings Environmental impact included tree and plant damage Toxic gas exposure with noticeable effects might be possible if wind direction unfavourable. Evacuations might be necessary. AEGL-2 and AEGL-3 (10 minutes, 30 minutes, 60 minutes) were used to assess consequences. EFFECTS was used for consequence modelling
Likelihood of occurrence	Initiating events included structural failure. Other details were not assessed or reported
Risk presentation	Different types of risks assessed were people or individual risk, environment, asset and reputation. Qualitative (Hazard and Operability (HazOp) analysis) and semi-quantitative (Hazard identification (HazId)) risk assessment were conducted. Risk matrix was used Severity levels used in risk matrix were: severe; major; moderate; minor; minimal Likelihood levels used in risk matrix were: extremely unlikely; very unlikely; possibility of occurring sometime; likely; very likely

Key information	*Description*
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Gas detectors, alarms; SIS included level and temperature control, safety automation, remote control of valves; Prevention measures included operator instructions, planning of pipeline routes, traffic planning; Protection measures included escape masks, extinguishing water systems, backup powder machine at ammonia storage, diesel powdered fire water pump, water curtain; Internal and external emergency plans

3. Hungary

The site is approximately 85,000 m2, is used as a food product plant and is located within 100 m of both residential and industrial areas (see table 13 for case study summary).

Table 13.
Hungary ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Liquefied ammonia releases from overpressurized pipeline. No transboundary effects considered plausible
Release effects and consequence considerations	As worst-case scenario, results for toxic gas released were studied. Scenario for risk assessment is as follows: a 30 m long, 150 mm internal diameter ammonia pipeline ruptures. Release location is 12 m high. Through rupture, 4,400 kg of liquified ammonia released (overpressure is 12.5 bar). The complex quantitative risk analysis deals with all possible weather circumstances. For following consequence considerations, 1 m/s windspeed and F-Pasquill stability class was defined (very stable condition) It was assessed that there would be: 10 per cent fatality - 1 person; 1 per cent fatality - 4 persons; environmental impact included toxic gas release to atmosphere Surrounding residential areas would require evacuation due to toxic release. Probit calculation method used to define lethality probability The Green Book[68] was used as reference for consequence modelling. Safeti was used for consequence modelling (see figures 16 and 17)
Likelihood of occurrence	Initiating events included structural failure, process control failure, technological problems, and domino effects from other installations Reference Manual Bevi Risk Assessments[69] and Purple Book used to determine likelihood of incident. Frequency of pipeline rupture used was 10^{-7}/meter/year

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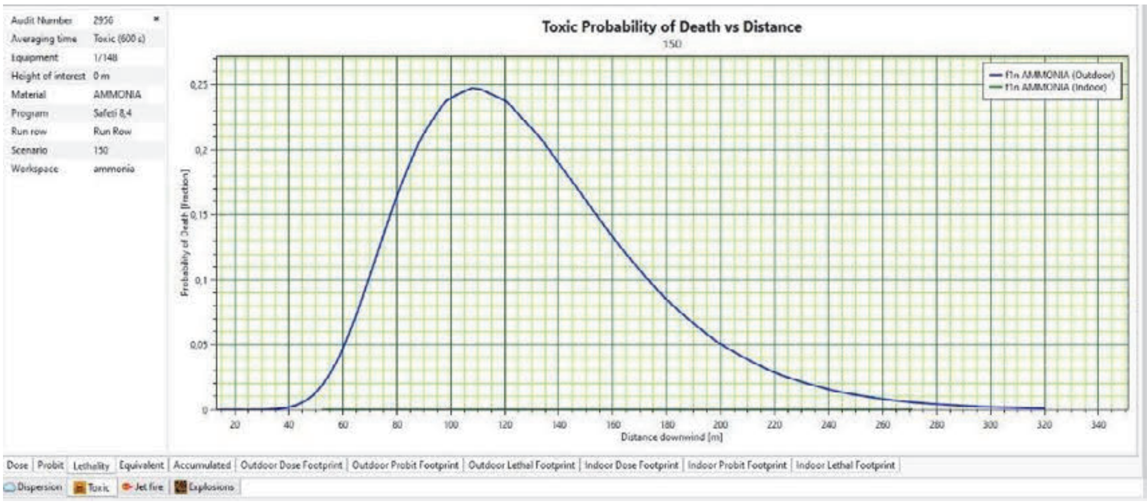
[68] C.J.H. van den Bosch and others, CPR 16E – Methods for the determination of possible damage to people and objects resulting from releases of hazardous materials: "Green Book" (n.p., CPR, 1992).

[69] Available at http://infonorma.gencat.cat/pdf/AG_AQR_2_Bevi_V3_2_01-07-2009.pdf.

Key information	*Description*
Risk presentation	Comprehensive risk assessment of establishment refers to all possible scenarios, including loss of containment of different containers, pipelines, and process vessels All scenarios that contribute significantly to location-specific risk and/or societal risk were included in quantitative risk analysis, defined as meeting following two conditions: frequency of the scenario $\geq 10^{-9}$ per annum; lethal injury (1 per cent fatality) can also occur outside site boundary Risk matrix was not used for risk assessment. Risk presentation included following: weather matrix (wind speed, wind direction, stability); risk ranking report; individual and societal risk (see figures 18 and 19)
Risk acceptability criteria	Acceptable and unacceptable zones were based on risk level and number of deaths (see figure 20) Different criteria were used for human and environmental risks. Environmental risk criteria used were qualitative as regulations provided only practical guidance. Stakeholders involved included operator and licensed consultants
Risk reduction measures implemented*	Toxic gas detectors and alarm systems installed; SIS included level, pressure and temperature control; Preventative measures included mobile water curtain nozzle system; Supplementary Information Request at the National Entries system is in place; Internal and external emergency plans are in place

Figure 16.

Hungary ammonia toxic probability of death versus distance

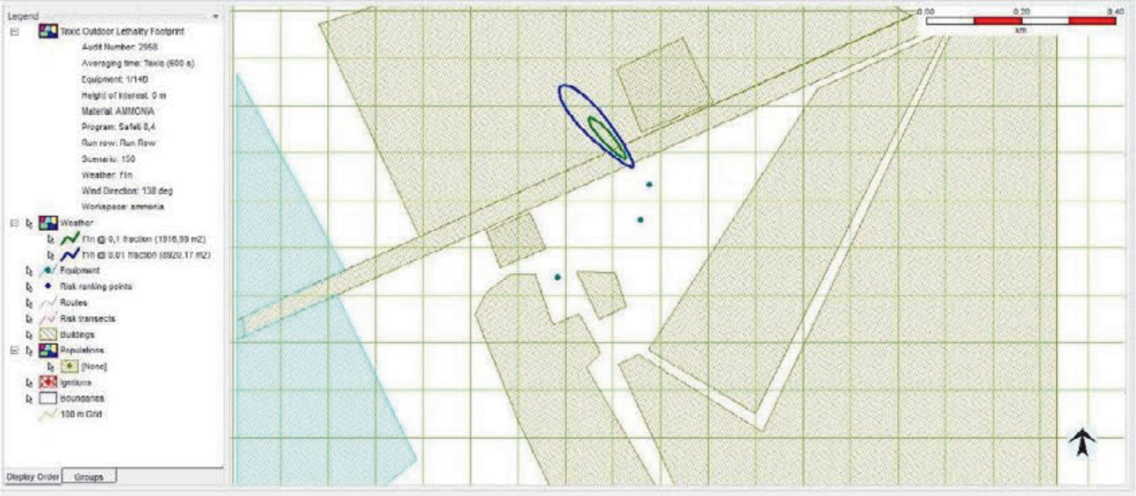


Audit Number	2956
Averaging time	Toxic (600 s)
Equipment	1/148
Height of interest	0 m
Material	AMMONIA
Program	Safeti 8,4
Run row	Run Row
Scenario	150
Workspace	ammonia

Sources: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 17.

Hungary ammonia map of 1–10 per cent toxic lethality curves

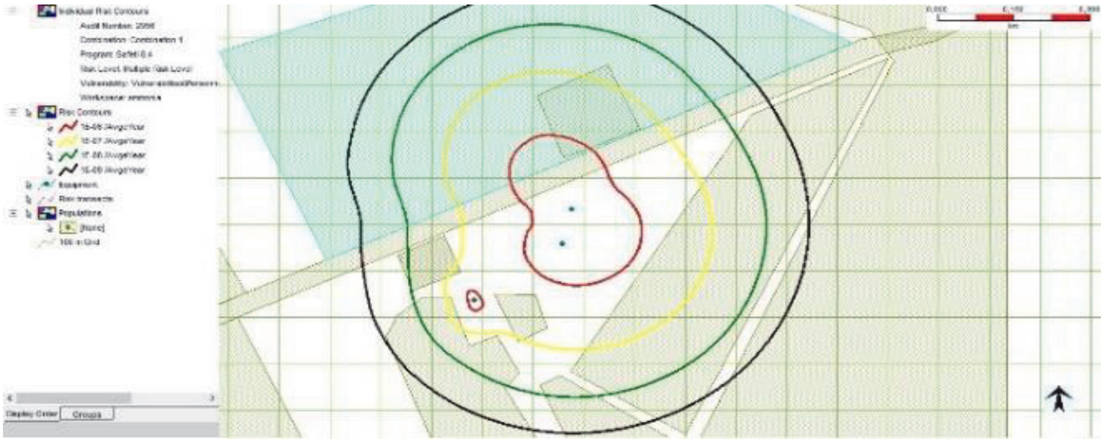


Audit Number: 2958
Averaging time: Toxic (600 s)
Equipment: 1/14D
Height of interest: 0 m
Material: AMMONIA
Program: Safeti 8,4
Run row: Run Row
Scenario: 150
Weather: f1n
Wind Direction: 138 deg
Workspace: ammonia

Sources: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

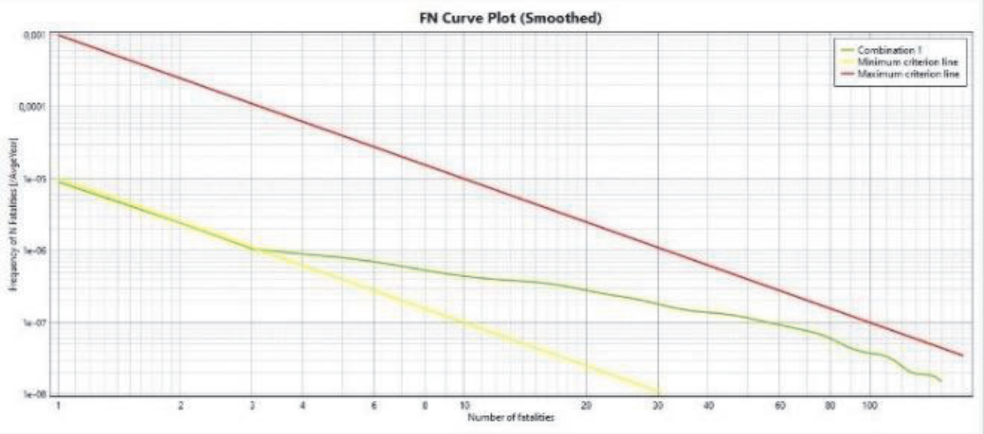
Figure 18.

Hungary ammonia individual risk contours



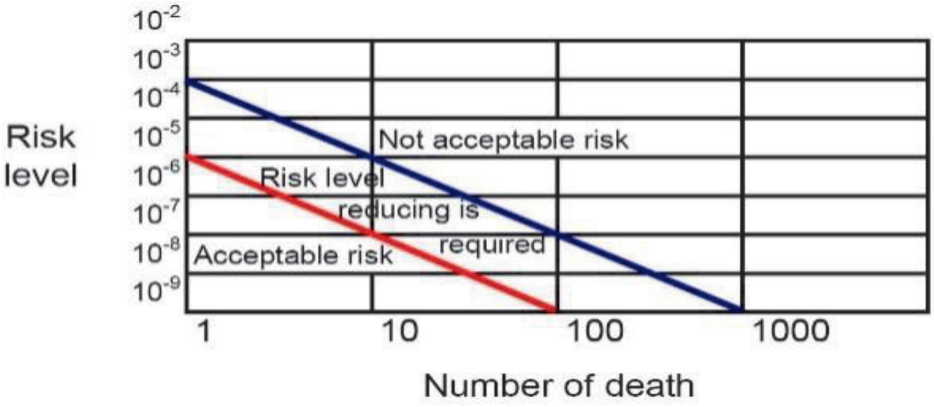
Sources: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 19.
Hungary ammonia societal risk FN curve



Sources: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 20.
Hungary ammonia risk acceptance criteria



Sources: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

4. Switzerland (transboundary)

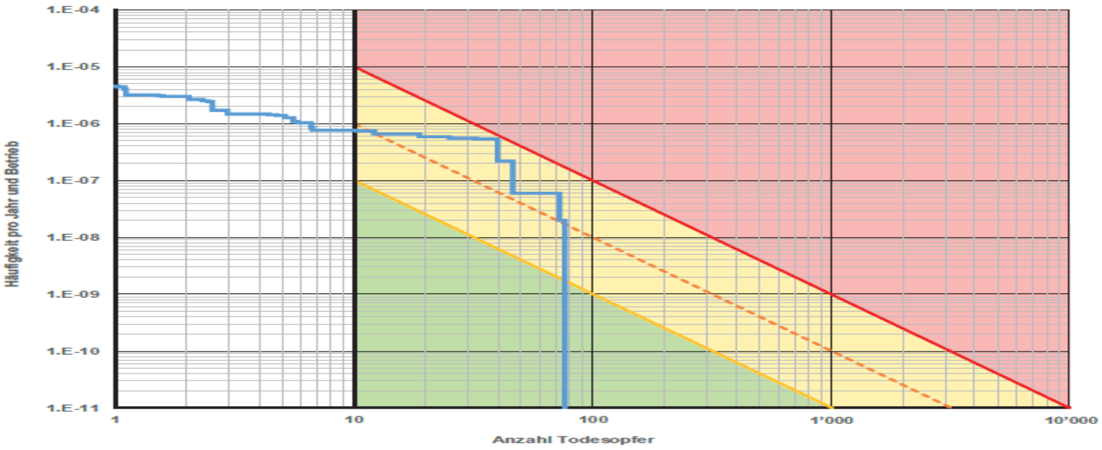
The facility area is approximately 29,100 m2 and is located close to a residential area, school and industrial area. A transboundary exposure in France was considered, as the border is 170 m from the facility (see table 14 for case study summary).

Table 14.
Switzerland (transboundary) ammonia refrigeration case study summary

Key information	*Description*
Major incident scenarios	Toxic ammonia leak from facility, with potential transboundary exposure in France (car park). Depending on scenario, liquified or gaseous ammonia can be released
Release effects and consequence considerations	Worst case scenario considered 80 fatalities in Switzerland and France. Number of transboundary fatalities not specifically calculated. Toxic gas exposure evaluated using EFFECTS lethal Probit function

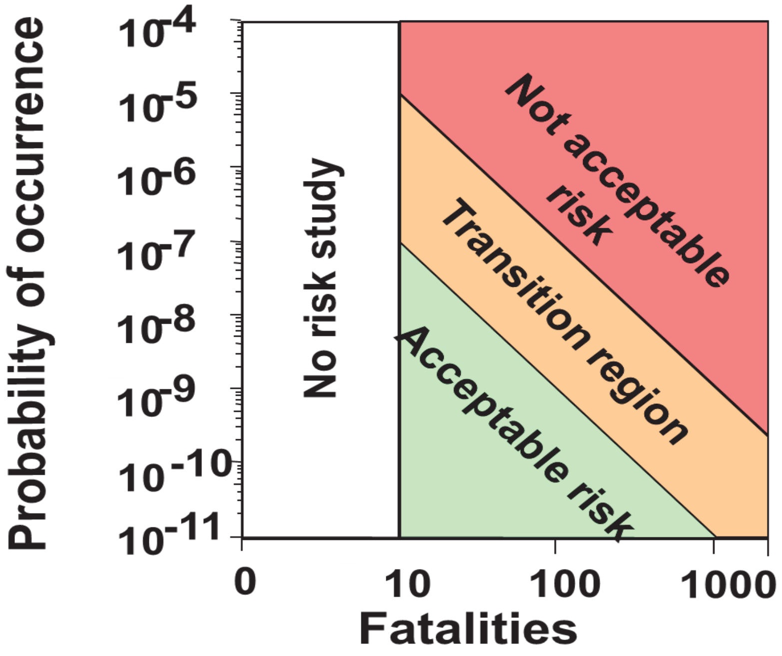
Key information	*Description*
Likelihood of occurrence	Initiating events included earthquake, fire, sabotage, mechanical action, mismanipulation, and spontaneous container failure. Likelihoods evaluated using Centre for Chemical Process Safety *Guidelines for Chemical Process Quantitative Risk Analysis* and other literature
Risk presentation	Societal risk was assessed quantitatively using fault tree analysis (FTA) and event tree analysis (ETA). Risk matrix was used where grey and green represented acceptable risk, yellow required assessment after weighing of interests, and red represented unacceptable risk. Relevant stakeholders are federal and cantonal authorities and representatives of different industrial associations (see figure 21)
Risk acceptability criteria	See figure 22
Risk reduction measures implemented*	Ammonia detectors, quick-acting valves, direct alarms to fire brigade; SIS included temperature and pressure control; Internal emergency plans
Additional risk reduction measures implemented	Prevention measures included heat exchanger for recooling (2 circuits), reduction of hazard potential (amount of ammonia); Building seismic retrofit; School about 150 m away has ammonia sensors

Figure 21.
Switzerland (transboundary) ammonia risk presentation



Sources: H. Bossler, Cantonal Laboratory of Canton Basel-Stadt, Switzerland, 2021

Figure 22.
Switzerland (transboundary) ammonia risk acceptance criteria



Sources: M. Merkofer et al., Evaluation criteria, Federal Office for the Environment, Switzerland, 2018 https://www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/beurteilungskriterien-zur-stoerfallverordnung-stfv.html

Note: White and green level: "Acceptable risk"; Orange level: "Transition region" acceptable after weight of interests; Red level: "Not acceptable risk". In Switzerland, the same quantitative acceptability criteria are also applied for environmental risks. Another X-axis is used instead of the fatalities.

C. Oil terminals

1. Germany

The site is located near a residential area. The site area and other details were not reported (see table 15 for case study summary).

Table 15.
Germany oil terminals case study summary

Key information	*description*
Major incident scenarios	Tank fire
Release effects and consequence considerations	Personnel injuries. Nearby people and buildings are exposed to radiation (1.6 kW/m^2, 5 kW/m^2 and 8 kW/m^2) due to tank fire. The Yellow Book[70] was used for consequence modelling along with DISaster MAnagement software (Germany) and Programme for Numerical Safety Simulations (Germany) Handbooks

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[70] C.J.H. van den Bosch and R.A.PM. Weterings, eds., *CPR 14E – Methods for the calculation of physical effects due to releases of hazardous materials (liquids and gases): "Yellow Book"* (n.p., CPR, 1996). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS2.html.

Key information	*description*
Likelihood of occurrence	Professional experience and judgement were used to determine likelihood of incident
Risk presentation	Risk to people (individual risk) was identified in risk assessment. Qualitative risk assessment was conducted using German checklist procedure (Association of Technical Inspection Agencies)
Risk acceptability criteria	Determined based on qualitative risk levels
Risk reduction measures implemented*	Fire detection alarms, emergency response plans

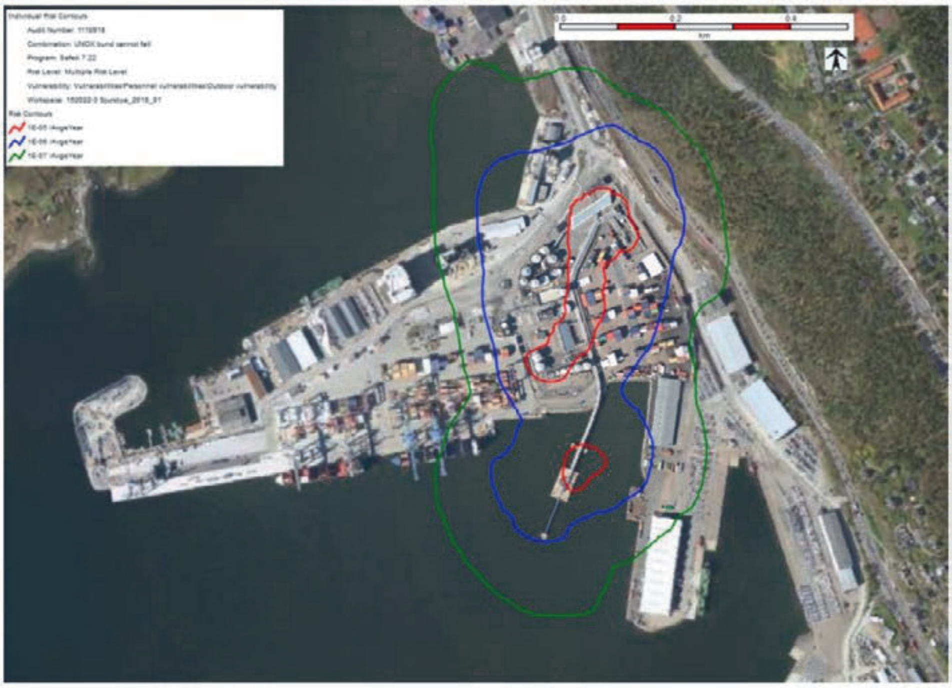
2. Norway

The site is approximately 30,000 m2, with a facility area of 700 m2, and is in a port area close to downtown (residential areas, recreation areas, other port activities), a main road and a railroad (see table 16 for case study summary).

Table 16.
Norway oil terminals case study summary

Key information	*Description*
Major incident scenarios	Flammable gas/liquid release due to leak of petroleum liquids resulting in fire or explosion. Quantitative risk analysis considered 13 scenarios, with most scenarios resulting in leak of petroleum and ignition of release, resulting in fire or explosion. Transboundary effects not possible for this scenario
Release effects and consequence considerations	Individual risk and society risk were considered. No population (public) outside port area would be affected. Environmental impact not covered in the assessment. Phast and Safeti 7.2 used
Likelihood of occurrence	Based on individual risk isocurves, a probability of 10^{-5}/year was determined inside oil terminal area and in small fraction of port area. A probability of 10^{-6}/year was determined mainly inside port area and partially extending beyond site to main road and railroad. The likelihood was determined from historical data from Phast and Safeti 7.2 and Reference Manual Bevi Risk Assessments
Risk presentation	Individual risk due to personnel exposure was identified in risk assessment. Quantitative risk assessment conducted using ETA (see figure 23)
Risk acceptability criteria	Risk acceptance criteria were based on guidelines from national authorities – Norwegian Directorate for Civil Protection. Risk assessment covered only human risk
Additional risk reduction measures implemented	Risk reduction and preventative measures implemented included gas detection with automatic emergency stop, sprinkler system for foam and water on loading rack, liquid detection in pump area with automatic emergency stop. Emergency response plan was distributed to relevant local emergency authorities

Figure 23.
Norway oil terminal individual risk contours



Sources: Tom Ivar Hansen, senior principal engineer at the Norwegian directorate for Civil Protection, DSB.

3. Serbia (transboundary)

The site is approximately 710,000 m2, with a facility area of 10,000 m2, close to industrial and residential areas and a river. A transboundary exposure in Romania was considered (see table 17 for case study summary).

Table 17.
Serbia (transboundary) oil terminals case study summary

Key information	*Description*
Major incident scenarios	Transboundary (Romania) river pollution possible with failure of preventative and response measures, resulting from petroleum product discharge due to barge collapse (loading/unloading pier)

Key information	*Description*
Release effects and consequence considerations	No fatalities or injuries estimated. However, there will be environmental impact due to river pollution. Oil slicks on water disrupt exchange of oxygen, moisture and heat between hydrosphere and atmosphere and prevent penetration of sunlight into water Consequences were determined based on Fay model of oil slick spread.[71] Width of oil slick was calculated to be 265 m (oil slick diameter) and speed of its movement on surface of water during spill was calculated to be 3 km/hour. Expected pollution time was 12.5 hours. Volume of oil evaporating was 287 m^3 and oil deposited on coast was 660 m^3 Joint management study of transboundary emergencies from spills of hazardous substance into Danube River was used to assess consequences of this scenario
Likelihood of occurrence	Initiating event was collapse of the barge (loading/unloading pier). Databases used for determining likelihood were ARAMIS D1C-APPENDIX 10 – Generic frequencies data for critical events. Likelihood of barge collapse was determined to be 1.55 x 10^{-5}/year
Risk presentation	Risk to environment (river) was identified in risk assessment. Semi-quantitative risk assessment was conducted using ARAMIS methodology and the methodology for drafting safety report and the accident protection plan Quantitative levels of severity were used in risk matrix (see table 18) Likelihood categories used in risk matrix were: low (<10^{-2}/year); medium (10^{-1} to 10^{-2}/year); high (1 to 10^{-1}/year)
Risk acceptability criteria	Risk assessment includes determination of occurrence likelihood, assessment of possible consequences and qualitative determination of risk (available tiers are negligible, low, medium, high and very high). Risk is considered unacceptable if it is assessed as “very high risk” per the risk matrix. Stakeholders involved in determining risk matrix were facility management and safety professionals
Risk reduction measures implemented*	Manual intervention by operator; Prevention measures include following operations and health/safety/environmental procedures; Protection measures include floating absorbers and skimmers; Emergency preparedness and response planning was established at facility; Instructions for safe work with dispersant for neutralization of spilled petroleum products on water surface of manipulative surfaces were implemented. Instructions for work with equipment for accident situations at river junction

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[71] J.A. Fay, “The Spread of Oil Slicks on a Calm Sea” in *Oil on the Sea*, D.P. Hoult, ed. (New York, Springer, 1969), pp. 53– 63.

Table 18.
Quantitative levels of severity used in risk matrix

Severity	*Dead animals (tons)*	*Contaminated soil (hectares)*	*Material damage (Serbian dinar/€)*
Low	≤0.5	≤0.1	≤100 000/850
Significant	0.5–5	0.1–1	100 000–1 million/850–8 500
Serious	5–10	1–10	1 million–10 million/8 500–85 000
Severe	10–30	10–30	10 million–100 million/85 000–850 000
Catastrophic	>30	>30	>100 million/850 000

4. Slovenia

The site is approximately 250,000 m2 and is located near industrial and residential areas, a river and the sea (see table 19 for case study summary).

Table 19.
Slovenia oil terminals case study summary

Key information	*Description*
Major incident scenarios	Fire scenario. Spillage of fuel from storage tank into retention pool, ignition and fire spread to another tank
Release effects and consequence considerations	Fatalities or injuries due to fire. Environmental effects involve emissions into air. People in areas surrounding facility exposed to toxic gases, adjacent building exposed to overpressure and radiation due to fire. No transboundary effects expected. Methodology from the SLO Guidelines for hazard identification and risk assessment[72] was applied. BREEZE was used for consequence modelling
Likelihood of occurrence	Initiating events were determined to be tank failure, ignition and failure of cooling systems. Likelihood of the incident was determined to be 7.6x10^{-14}/year. Red Book[73] was used as reference. Likelihood of failure of cooling systems was 6.9×10^{-2} /year, tank failure: 1.1×10^{-9} /year
Risk presentation	Individual risk due to personnel exposure was identified in risk assessment. Quantitative risk assessment was conducted using consequence modelling. Qualitative methods used for conducting risk assessment were HazOp, HazId and risk assessment Qualitative severity levels were used: Insignificant: no injuries to employees in facility or nearby occur and/or minor damage to machine or device occurs and/or inadequate batch and/or environmental damage is insignificant Small: minor injuries to employees and/or damage to individual machinery and/or minor production downtime and/or minor environmental pollution Serious: individual fatal injuries or serious injuries to employees or in immediate vicinity and/or significant destruction of facility and/or

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[72] See https://www.gov.si/assets/ministrstva/MOP/Dokumenti/Industrijske-nesrece/c93c587d86/pripravljenost_na_nesrece.pdf (Slovenian).

[73] J.C.H. Schüller and others, *CPR 12E – Methods for determining and processing probabilities: "Red Book"* (n.p., CPR, 1997). Available at https://publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS4.html.

Key information	*Description*
	major production downtime and/or environmental damage, but consequences not long lasting Catastrophic: more fatal injuries and/or serious injuries to employees or residents and/or complete destruction of facility and/or other facility may be affected and/or surrounding population may be endangered and/or injuries may occur environment with longer-term consequence Qualitative likelihood levels were used: insignificant; small; moderate; high
Risk acceptability criteria	Risk considered acceptable if assessed as such by applying criteria from risk matrix. Stakeholders involved in determining risk matrix were facility management and safety professionals
Risk reduction measures implemented*	Fire alarm, infrared flame detector, video surveillance system, visual and audible alarm; SIS included lightning protection, double bottom tanks, connection of extinguishing agent, restraint system, overpressure protection with safety valves, fire embankment, bottom leak control; Prevention measures included level control, temperature gauges, anti-overfill control; Protection measures included automated control system for extinguishing and cooling; Emergency response plans for protection and rescue plan for accidents with hazardous substances

D. Ammonium nitrate storage

1. Estonia

The site is approximately 85,000 m2, contains an ammonium nitrate and ammonium nitrate-based fertilizer storage facility at a port, and is located near a residential area and the sea (see table 20 for case study summary).

Table 20
Estonia ammonia nitrate storage case study summary

Key information	*Description*
Major incident scenarios	Explosion due to cargo contamination with foreign impurities than can act as catalyst in self-decomposition process. Ammonium nitrate temperature will rise, resulting in fire and explosion. Transboundary effects not considered plausible
Release effects and consequence considerations	Fatalities or injuries due to explosion and fire. Environmental effects involve pollution due to release of combustion and decomposition products. Release of extinguishing water into sea can result in environmental contamination. There will be off-site damages as port and surrounding residential areas would need to be evacuated due to incident. Three types of zones are considered based on a trinitrotoluene equivalence formula (United Kingdom of Great Britain and Northern Ireland methodology)
Likelihood of occurrence	Initiating events were determined to be human error, technological problems, process control failure, external factors and natural hazards triggering technological disasters (Natech) risks. Likelihood was determined using HazOp and failure mode and effects analysis (FMEA) databases. Likelihood of occurrence of incident considered “very small” (i.e., annual likelihood was 0.005–0.05 per cent)

Key information	*Description*
Risk presentation	Individual and societal risk (people, surroundings, environment) and property loss were different risks considered. Semi-quantitative risk assessment was conducted using HazOp and FMEA methods. Consequence modelling was used for conducting risk assessment. Risk matrix was used for determining risk Qualitative severity levels were used: little importance; light; hard; very hard; catastrophic Qualitative likelihood levels were used: very small; small; middle; big; very big
Risk acceptability criteria	Not available
Risk reduction measures implemented*	Alarm system on and off-site; Preventative measures included fencing, following fire safety requirements, video surveillance system, temperature control system, warehouse ventilation, different alarms, maintenance and exercises; Protection measures included personal protective equipment, dome warehouse, fire extinguishers and fire alarm signalization; Internal and external emergency response plans for incident scenario

2. Latvia

The site consists of ammonium nitrate and ammonium nitrate-based fertilizer storage, and is located close to a railway and industrial area. The site area was not reported (see table 21 for case study summary).

Table 21.
Latvia ammonia nitrate storage case study summary

Key information	*Description*
Major incident scenarios	Loader or truck fire with ammonia toxic gas release. Transboundary effects not considered possible
Release effects and consequence considerations	There will be fatalities or injuries due to incident. Toxic effects of nitrogen oxides were considered by evaluating concentrations at heights of 1.5 m (considering individuals outdoors), and 5 m (considering building openings) Consequences include off-site damage, respiratory illness on exposure, fatalities, and other injuries. A 1 per cent lethality distance was used to measure consequences Purple Book used for consequence modelling
Likelihood of occurrence	Initiating event causes were determined to be human error and process control failure. Likelihood of incident determined using Red Book
Risk presentation	Individual and societal risk were considered. Qualitative risk assessment was conducted using FMEA methods. Quantitative risk assessment methods also considered and used
Risk acceptability criteria	Risk acceptability criteria for individual risk was 10^{-6}, following recommendations from the Netherlands
Additional risk reduction measures implemented	Limit on ammonium nitrate in one pile implemented as prevention measure Emergency response plan for incident

3. Netherlands

The site is an ammonium nitrate-based fertilizer production and ammonia storage facility of unknown size. Details regarding proximal exposures were not provided. The evaluated scenario is very similar to the case studies for ammonia refrigeration as the material and consequences are identical (see table 22 for case study summary).

Table 22.
Netherlands ammonia nitrate storage case study summary

Key information	*Description*
Major incident scenarios	Ammonia release scenarios are considered (tank failure, pipeline failure). Transboundary effects not expected in this case
Release effects and consequence considerations	Personnel fatalities outside facility premises are possible. Expected number of fatalities calculated using integral risk assessment models Environmental effects considered due to release. Probability of fatality and number of fatalities based on toxic Probit functions. an area where public is in danger calculated, based on intervention levels comparable to AEGL Consequence modelling based on Purple Book. New toxic Probit functions and toxic intervention levels used through RIVM website. Phast Safeti was used for consequence modelling
Likelihood of occurrence	Initiating events determined to be human error, process control failure and material degradation (corrosion). Red Book and Purple Book used as references to determine likelihood of incident
Risk presentation	Purple Book used to determine likelihood of incident Likelihood of catastrophic failure of a pressure vessel containing ammonia was 10^{-6}/year Hazards considered were exposure to toxic ammonia. Risk measures calculated were individual risk and societal risk. Area where people can be in danger is defined (exposure to concentrations indoors higher than life-threatening value). Quantitative risk assessment was conducted using standard set of scenarios and frequencies, combined with consequence modelling Risk matrix was not used. Risk summarized using Individual Risk and Societal Risk (FN-curve)
Risk acceptability criteria	Risk acceptability criteria determined per regulations: individual risk lower than 10^{-6}/year at location of houses; societal risk of $10^{-3}.N^{-2}$ /year. For societal risk graph, see Purple Book Criteria only for human risk, none for environmental risk Risk acceptability criteria was based on national legislative requirements
Additional risk reduction measures implemented	Risk assessment was used for off-site spatial planning, not to determine risk reduction measures. Measures should be implemented by company based on risk matrix and as approved by competent authorities

E. Chlorine

1. France

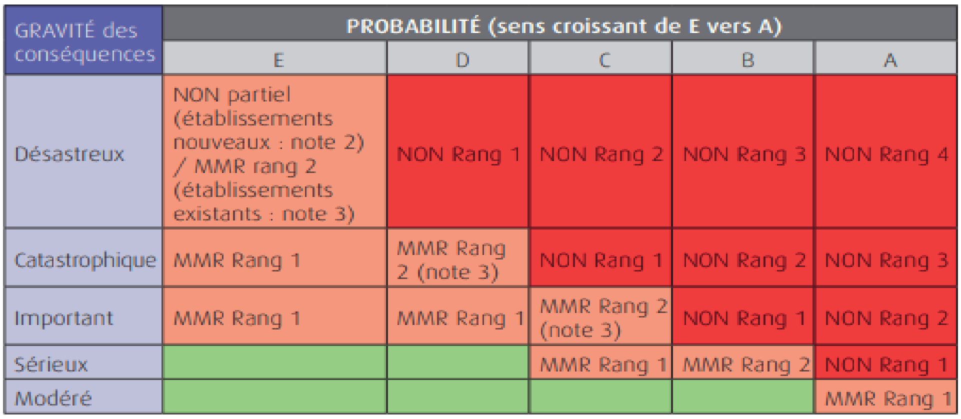
The site is approximately 560,000 m2 and is located near a railway, a motorway and two factories (see table 23 for case study summary).

Table 23.
France chlorine case study summary

Key information	*Description*
Major incident scenarios	Toxic chlorine gas release; No transboundary effects are considered plausible
Release effects and consequence considerations	Worst-case scenario considered two fatalities and 94 injuries in an “extremely unlikely” scenario. Toxic gas released into atmosphere would result in environmental effects National threshold values similar to IDLH were used. Consequence (gas dispersion) modelling was conducted using ALOHA, Phast and FLame ACceleration Simulator (FLACS), referencing national database published by French National Institute for Industrial Environment and Risks
Likelihood of occurrence	Initiating events included equipment failure. Likelihood was evaluated using proprietary database belonging to Arkema (DOROTE), Safecalc and EXE for failure of risk control measures (calculated between 10^{-2} and 10^{-3}/year failure rates) Incident likelihood for loss of containment events ranging from 5 seconds to 60 minutes ranged from 8.5×10^{-6} to 8.6×10^{-8}/year, respectively. A 60-minute duration pipe break evaluated at likelihood of 5.3×10^{-5}/year
Risk presentation	Individual risk due to personnel exposure to chlorine gas was estimated. Quantitative risk assessment was conducted using Bow-Tie analysis. Risk matrix was used for risk assessment Qualitative severity levels were used: Moderate: No injury or fatality; Serious: Minor injury/illness; Important: Hospitalization due to exposure/permanent disability; Catastrophic/Disastrous: Fatality Qualitative likelihood levels were also used: extremely unlikely; very unlikely; unlikely; likely; frequent
Risk acceptability criteria	Risk acceptance criteria were determined based on national criteria (Circular of 10 May 2010), using combination of qualitative and quantitative levels, i.e. considering gravity of scenario and associated probability. Table 24 provides an example of risk acceptability criteria Approaches for assessing human and environmental risks are different. Environmental impacts are considered using case-by-case qualitative approach Stakeholders involved in determining risk matrix and risk acceptance were facility management, safety professionals and local competent authority

Key information	*Description*
Risk reduction measures implemented*	Toxic gas detectors and alarm systems installed; Prevention measures included regular tightness tests, choice of steel pipes and seals, nitrogen flushing; Protection measures including use of wedges and brakes for chlorine wagons; Emergency response plans established for toxic gas release at facility involving surrounding facilities; Specific procedure developed to prevent water pollution

Table 24.
France chlorine risk acceptance criteria



GRAVITÉ des conséquences	PROBABILITÉ (sens croissant de E vers A)				
	E	D	C	B	A
Désastreux	NON partiel (établissements nouveaux : note 2) / MMR rang 2 (établissements existants : note 3)	NON Rang 1	NON Rang 2	NON Rang 3	NON Rang 4
Catastrophique	MMR Rang 1	MMR Rang 2 (note 3)	NON Rang 1	NON Rang 2	NON Rang 3
Important	MMR Rang 1	MMR Rang 1	MMR Rang 2 (note 3)	NON Rang 1	NON Rang 2
Sérieux	🟩	🟩	MMR Rang 1	MMR Rang 2	NON Rang 1
Modéré	🟩	🟩	🟩	🟩	MMR Rang 1

Source: Ministère de l'écologie, de l'énergie, du développement durable et de la mer, en charge des technologies vertes et des négociations sur le climat, "Circulaire Du 10 Mai 2010 Récapitulant Les Règles Méthodologiques Applicables Aux Études de Dangers, à l'appréciation de La Démarche de Réduction Du Risque à La Source et Aux Plans de Prévention Des Risques Technologiques (PPRT) Dans Les Installations Classées En Application de La Loi Du 30 Juillet 2003," May 10, 2010, https://www.legifrance.gouv.fr/download/pdf/circ?id=31313.

Note: "Gravité des consequences" means "Seriousness of consequences"; "Désastreux" means "Disastrous"; "Catastrophique" means "Catastrophic"; "Important" means "Major"; "Serieux" means "Serious"; "Modéré" means "Moderate"; "NON partiel (établissements nouveaux: note 2)" means "Partial NO (new establishments: note 2)"; "MMR rang 2 (établissements existants: note 3)" means "Risk Management Measure rank 2 (existing establishments: note 3"; "PROBABILITÉ (sens croissant de E vers A)" means "PROBABILITY (increasing order from E to A)".

2. Hungary

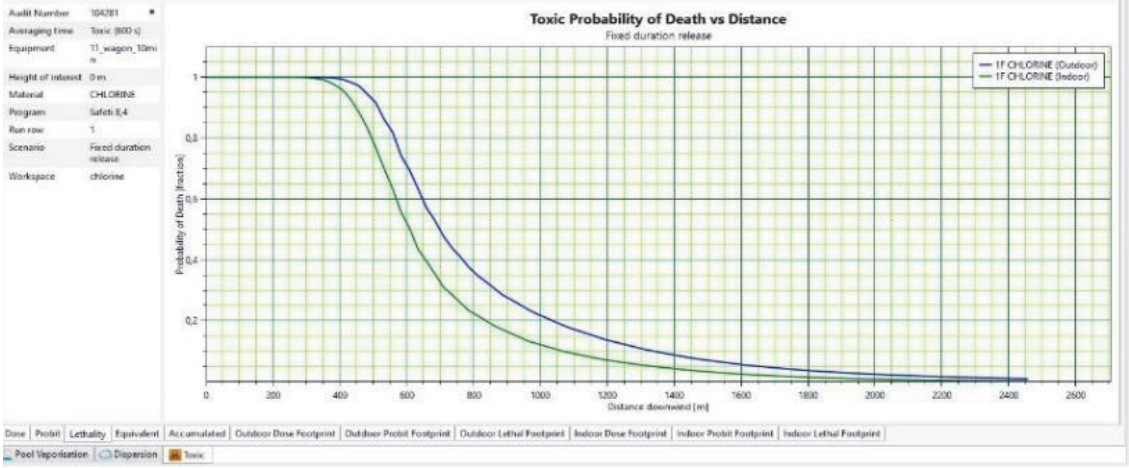
The site is approximately 33,500 m2, close to a residential area (300 m) and an industrial area (100 m) (see table 25 for case study summary).

Table 25.
Hungary chlorine risk acceptance criteria

Key information	*Description*
Major incident scenarios	Facility contains 40 m^3-volume tank wagon containing 50 tons of chlorine (fluid phase), under 4.2 bar overpressure (gauge). Three different release scenarios considered were catastrophic rupture, 10-minute release, and 10 mm leak. Worst-case scenario was a 10-minute release. No transboundary effects considered plausible in any scenario. Complex quantitative risk analysis deals with all possible weather circumstances; for following consequence considerations, 1 m/s windspeed and F-Pasquill stability class is defined (very stable condition)

Key information	*Description*
Release effects and consequence considerations	Personnel fatalities and injuries are expected. Consequences quantified as below: 100 per cent fatality: 0 person (~380m); 50 per cent fatality: 1,000 persons (~700m); 10 per cent fatality: 3,800 persons (~1,300m); 1 per cent fatality: 5,000 persons (~2,400m) Environmental effects expected due to toxic chlorine gas release in atmosphere. surrounding residential areas would need to be evacuated due to toxic release Probit calculation methods were used to define lethality probability. Green Book referred to for consequence modelling. Safeti 8.4 used for consequence modelling Consequence modelling outputs included toxic lethal curves for worst-case scenario (10 minute release of 50 tons chlorine, see figure 24) and map of various percentages of lethality for worst-case wind speed, wind direction and stability (see figure 25)
Likelihood of occurrence	Initiating events included structural failure and domino effects from other installations. Reference Manual Bevi Risk Assessments and Purple Book used to determine likelihood of incident. Frequency of release of entire contents in 10 minutes in continuous and constant stream liquified toxic gas was 5 x 10^{-6}/year
Risk presentation	Comprehensive risk assessment of establishment refers to all possible scenarios, including loss of containment of different containers, pipelines and process vessels. All scenarios that contribute significantly to location-specific risk and/or societal risk were included in quantitative risk analysis, defined as meeting following two conditions: frequency of the scenario $\geq 10^{-9}$ per annum; lethal injury (1 per cent fatality) can also occur outside site boundary Risk matrix was not used for risk assessment. Risk presentation included following: weather matrix (wind speed, wind direction, stability); risk ranking report; individual and societal risk as presented in figure 26 and figure 27
Risk acceptability criteria	Risk acceptability criteria consisted of acceptable and unacceptable zones based on risk level and number of deaths (see figure 28) Different criteria were used for human and environmental risks. Environmental risk criteria used were qualitative, as regulations provided only practical guidance. Stakeholders involved included operator and licensed consultants
Risk reduction measures implemented*	Toxic gas detectors and alarm systems; SIS: Level, pressure and temperature; Preventative measures include fixed water curtain nozzle system installed around tank-wagon offloading place (~20x5 m), system is manually checked periodically; Internal and external emergency plans are put in place

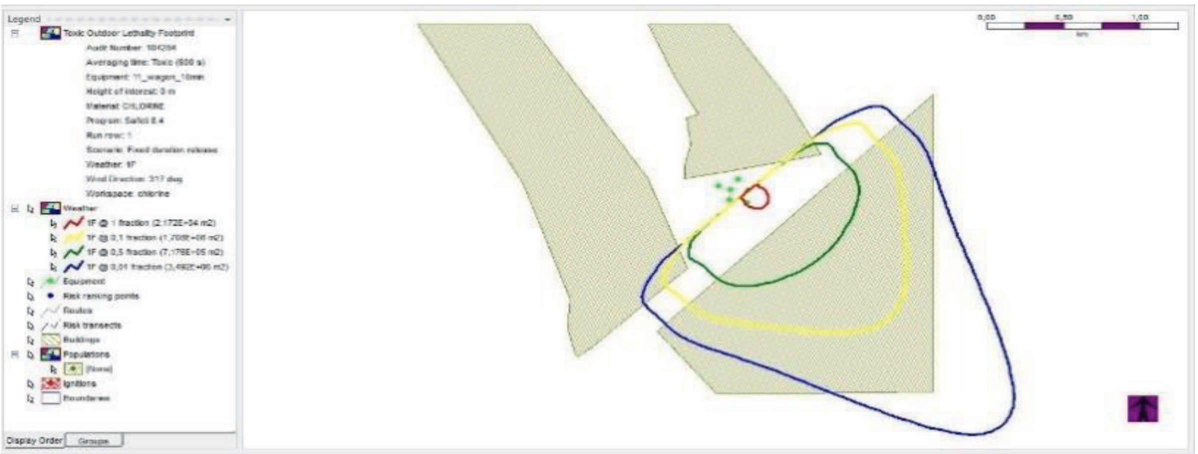
Figure 24.
Hungary chlorine toxic probability of death versus distance



Audit Number	104281
Averaging time	Toxic (600 s)
Equipment	11_wagon_10min
Height of interest	0 m
Material	CHLORINE
Program	Safeti 8,4
Run row	1
Scenario	Fixed duration release
Workspace	chlorine

Source: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 25.
Hungary chlorine map of 1 per cent, 5 per cent, 50 per cent and 100 per cent lethality curves

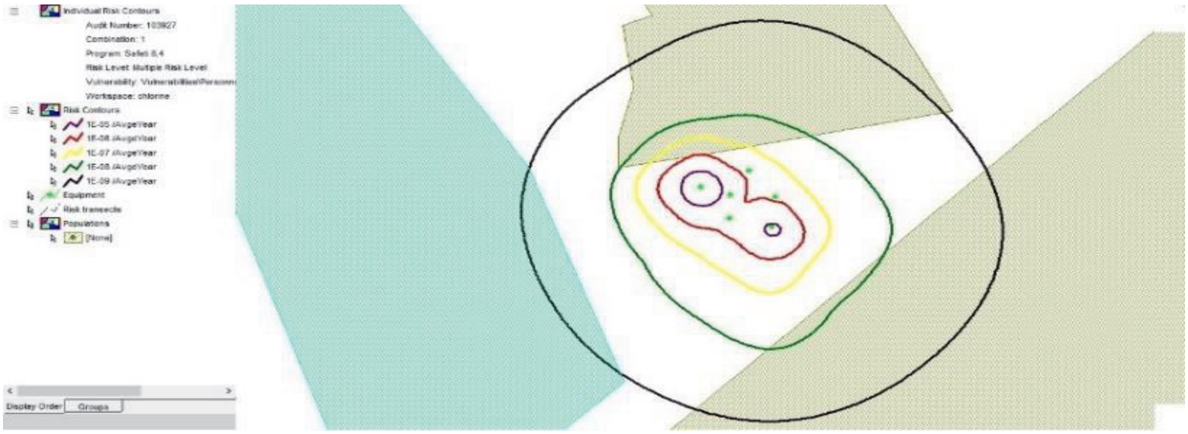


Toxic Outdoor Lethality Footprint
Audit Number: 104284
Averaging time: Toxic (600 s)
Equipment: 11_wagon_10min
Height of interest: 0 m
Material: CHLORINE
Program: Safeti 8.4
Run row: 1
Scenario: Fixed duration release
Weather: 1F
Wind Direction: 317 deg
Workspace: chlorine

Weather
1F @ 1 fraction (2.172E+04 m2)
1F @ 0,1 fraction (1,708E+06 m2)
1F @ 0,5 fraction (7,178E+05 m2)
1F @ 0,01 fraction (3,492E+06 m2)
Equipment
Risk ranking points
Routes
Risk transects
Buildings
Populations
[None]
Ignitions
Boundaries

Source: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 26.
Hungary chlorine individual risk contours

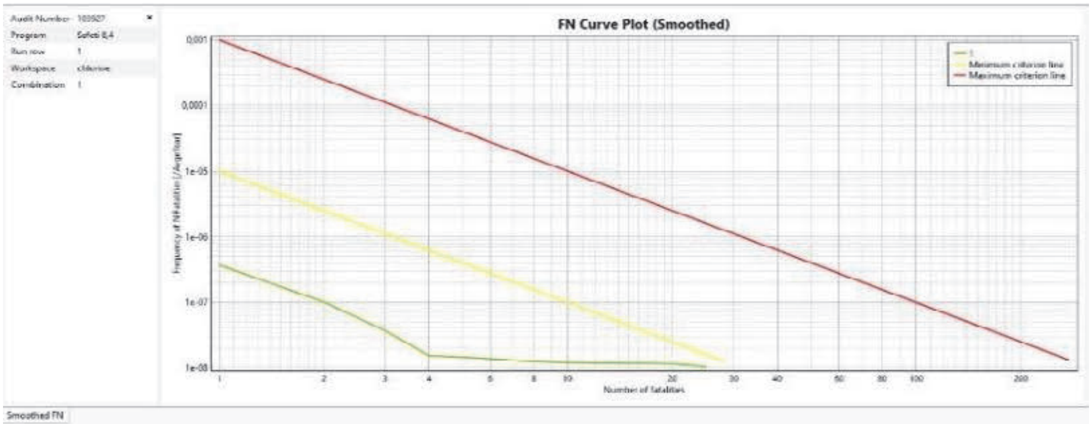


Individual Risk Contours
Audit Number: 103927
Combination: 1
Program: Safeti 8,4
Risk Level: Multiple Risk Level
Vulnerability: Vulnerabilities\Personn
Workspace: chlorine

Risk Contours
1E-05 /AvgeYear
1E-06 /AvgeYear
1E-07 /AvgeYear
1E-08 /AvgeYear
1E-09 /AvgeYear
Equipment
Risk transects
Populations
[None]

Source: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

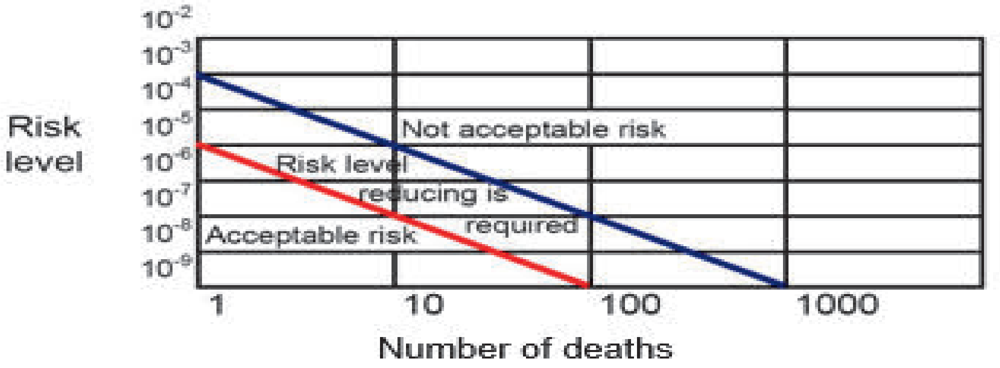
Figure 27.
Hungary chlorine societal risk F-N curve



Audit Number 103927
Program Safeti 8,4
Run row 1
Workspace chlorine
Combination 1

Source: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

Figure 28.
Hungary chlorine risk acceptance criteria



Source: Iván Domján, National Directorate General for Disaster Management, Hungary, October 2022.

3. Switzerland (transboundary)

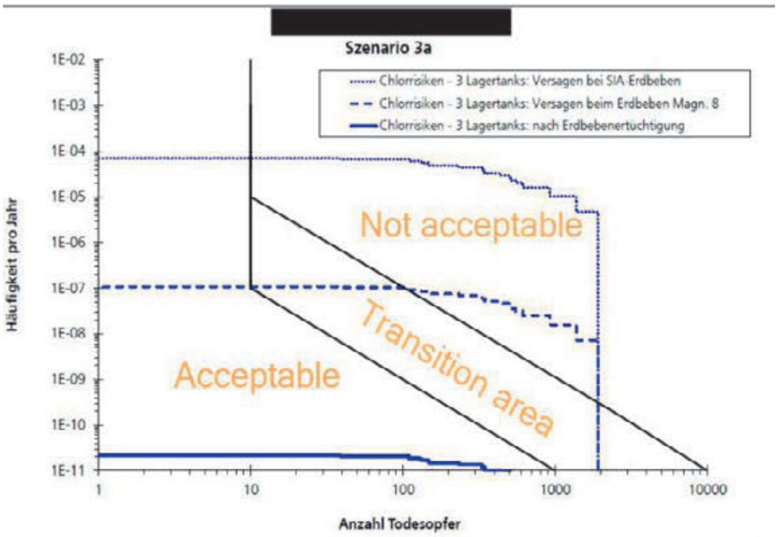
The site is approximately 160,000 m2 and consists of a former chlor-alkali electrolysis facility in an industrial park. Details regarding proximal exposures were not provided. A transboundary exposure in Germany was considered (see table 26 for case study summary).

Table 26.
Switzerland (transboundary) chlorine risk acceptance criteria

Key information	*Description*
Major incident scenarios	Toxic chlorine gas release due to different scenarios. Worst-case scenario was earthquake destroying chlorine storage tanks. Transboundary effects are considered possible and can affect Germany. Neighbouring country has been notified
Release effects and consequence considerations	2,000 fatalities were estimated during risk assessment. In the case of an earthquake, no evacuation would be possible, due to large-scale destruction of civil buildings and infrastructure. Affected area in Germany not populated, so no quantitative assessment of transboundary damage was conducted Consequence modelling was conducted using EFFECTS

Key information	*Description*
Likelihood of occurrence	Identified cause of incident was earthquake Swiss Society of Engineers and Architects (SIA)-Norm was used for determining likelihood of occurrence. Likelihood of SIA-earthquakes in area approximately 10^{-3}/year (once every 475 years)
Risk presentation	Societal risk due to personnel exposure to chlorine gas. Quantitative risk assessment was conducted using FTA and ETA Risk matrix was used for risk assessment. Quantitative severity levels used in risk matrix were based on number of fatalities. Quantitative likelihood levels used in risk matrix ranged from 10^{-1}/year to 10^{-10}/year (see figure 29)
Risk acceptability criteria	The Swiss Federal Office for the Environment provides a document with quantitative societal risk acceptance criteria. Different criteria were used for human and environmental risk evaluation. Stakeholders involved in determining risk matrix included facility management and facility safety professionals Risk acceptability criteria consisted of three different zones: “Acceptable,” “Transition Area” and “Not Acceptable,” depending on frequency of incident per year (Y-axis) and number of fatalities (X-axis) (see figure 29) In Switzerland, same quantitative acceptability criteria also applied for environmental risks. Another X-axis is used instead of fatalities
Additional risk reduction measures implemented	Earthquake retrofitting of storage building and second barrier concept; Emergency response plans established for toxic gas release at facility, for example, sodium thiosulfate added to sprinkler system and a special fire truck

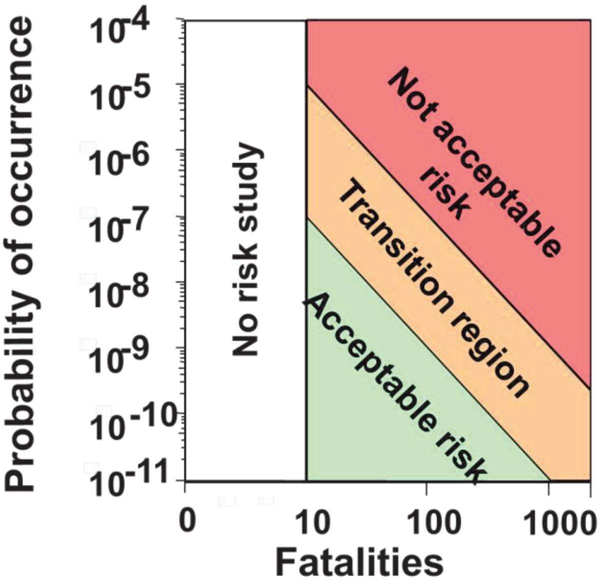
Figure 29.
Switzerland (transboundary) chlorine risk presentation



Source: G. Stebler, Office for Environmental Protection, Canton Basel-Landschaft, Switzerland 2001

Note: “Häufigkeit pro Jahr” means “Frequency per year”; “Anzahl Todesopfer” means “Number of fatalities”; Szenario 3a” means “Scenario 3a”; “Chlorrisiken” means “Chlorine risks”: “Lagertanks” means “Storage tanks”; “Versagen bei SIA-Erdbeben” means “Failure at SIA-Earthquake”; “Versagen beim Erdbeben Magn. 8” means “Failure at magnitude 8 earthquake”; “nach Erdbebenertüchtigung” means “after seismic retrofitting”.

Figure 30.
Switzerland (transboundary) chlorine risk acceptance criteria



Source: M. Merkofer et al., Evaluation criteria, Federal Office for the Environment, Switzerland, 2018 https://www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/beurteilungskriterien-zur-stoerfallverordnung-stfv.html

IV. Key findings

Risk assessment methodologies used in 18 case studies from UNECE countries, including transboundary examples from Serbia (oil terminal) and Switzerland (ammonia refrigeration and chlorine), were discussed in this report. The case studies were analysed based on five different facility types: LPG/LNG, ammonia refrigeration, oil terminals, ammonium nitrate storage and chlorine.

The following are some important comparisons and differences based on the risk assessment case studies:

(a) Similarities: For most case studies, there were similarities in the nearby exposure targets, databases, resources for determining risk assessment parameters such as severity and likelihood, and software used for consequence modelling;

(b) Facility type: The facility type determines the primary hazardous material of interest and thus is the driving factor impacting the type of consequence but was not a contributing factor to most of the other evaluated parameters such as environmental considerations, type of risk assessment conducted, tools used, or databases referenced. The facility scale and proximity to populated targets had more of an impact on the magnitude of consequences than the facility type;

(c) Scale: The selection of case studies covered a considerable range in scale (1,000–600,000 m^2);

(d) Incident causes: Some common incident causes considered in these assessments were human error, structural failure, equipment failure, technological failures, process control failures, natural disasters (earthquakes, thunderstorms). The type of facility did not seem to affect the incident cause significantly. The causes were more likely dependent on the exact incident scenario considered. Human error was not listed as a discrete initiating event in all scenarios;

(e) Likelihood: Initiating event likelihoods ranged considerably from 10-2/year to 10-14/year;

(f) Consequence modelling: Several case studies conducted consequence modelling to determine the onsite and off-site effects due to heat radiation, toxic dispersion levels and explosion radii. Consequence modelling, when employed, utilized a small cut set of available software platforms including Phast Safeti, EFFECTS, ALOHA and BREEZE. The annex to the present document summarizes many other commercially available software platforms and their applications. The common use of fewer software packages may allow for easier transferability and understanding of results across diverse stakeholders;

(g) Databases: Databases and references for consequence modelling included the Purple Book, the Green Book and the Yellow Book. General databases and references used for determining likelihood of incident included the Red Book and the Purple Book:

   a. Country-specific databases included RIVM, the Classification of Hazardous Locations, the Association of Technical Inspection Agencies checklist procedure (Germany), the Administration Research Actions Management Information System database (Switzerland), the Poland and Hungary Assistance for the Restructuring of the Economy guidelines, the Swiss Society of Engineers and Architects-Norm and the Arkema proprietary database;

   b. The "coloured books" (Green Book, Yellow Book, Purple Book, Red Book) and RIVM appear to be common references widely used across different countries;

(h) Risk presentation: Most case studies used a risk matrix to present findings. Both qualitative and quantitative risk assessment methods were used in almost every case study. Most of the incident scenarios considered for risk assessment were events having low likelihood of occurrence. The risk matrices used had 3-5 severity and likelihood levels, which appeared to be the norm for risk assessments for the United Nations Economic Commission for Europe (UNECE) countries. The magnitudes of severity and likelihood levels depended on the type of risk matrix used and were highly dependent on the stakeholders involved and the selected risk acceptance criteria. Case studies that did not use a risk matrix had defined risk acceptance criteria based on severity and likelihood of the incidents, which is indicative of a similar approach as in the risk matrix;

(i) Risk acceptance criteria: The risk acceptability criteria differed significantly depending on the country, company, locality and stakeholders involved, such as process safety professionals, facility management and operators, federal and legal authorities. Ultimately, risk acceptance criteria were observed to be highly dependent on two factors: the country regulations and the risk matrix developed by the stakeholders. For all types of installations, a few countries apply consequence limit values and others have tailor-made acceptability criteria based on the individual or societal risk, with acceptable and unacceptable zones dependent on the risk levels and fatalities, aligned with a risk matrix type evaluation;

(j) Environmental considerations: Most of the case studies had different criteria for human and environmental risks. Only very few countries take environmental effects quantitatively into account. The environmental risk criteria considered in most of the case studies were qualitative;

(k) Transboundary considerations: Very few case studies addressed transboundary effects. Where transboundary risk assessments are to be conducted, the choice of acceptance criteria and data sources for both likelihood and consequences should be agreed upon prior to conducting the risk assessment.

The learnings assimilated from these case studies can be used to improve existing risk assessment methodologies and facilitate sharing of ideas amongst the UNECE countries to enhance safety in facilities, their neighbours and the environment.

Annex – Available software

List of currently available software tools

This annex identifies software tools for the application of risk assessment. The lists presented in this annex are non-exhaustive and that other comparable tools are available, including discontinued and legacy software no longer supported by the publisher. The intent of this annex is to highlight the variety of options available for the various tasks within risk assessment.

I. Software tools for hazard analysis

While commercially available software tools specific to conducting hazard analysis are available, many entities develop their own file structures in word processing, spreadsheet, or database software (e.g., Microsoft Office platform).

The programmes listed in table A.1 provide a framework for conducting and documenting process hazard analysis, including the ability to build on previous studies.

Table A.1.
Software tools for hazard analysis

Name	*Hazop+*[74]	*PHA Pro*[75]	*PHA-Tool*[76]	*PHAWorks*[77]
Developer	Isograph	sphere	BakerRisk	Primatech
Purpose	HazOp	Process Hazard Analysis (various methods)		
Use	Document and manage process hazards			
Benefits	Supports HazOp method	Supports HazOp, What-If methods; assumptions register, change log. Customizable interactive risk matrix; ability to group recommendations		
Limitations	Other methods unavailable	Additional modules required for advanced analysis		
Availability	Licensed			

Abbreviations: HazOp, Hazard and Operability.

II. Software tools for event tree analysis/fault tree analysis

It should be noted that several commercially available software tools specific to developing fault tree analysis (FTA), event tree analysis (ETA) and linked reliability/failure mode and effects analysis (FMEA)/failure mode effects and criticality analysis (FMECA) are available, including free versions with limited functionality and cloud/web-based options (see table A.2).

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[74] Available at www.isograph.com/software/hazop/.

[75] Available at https://sphera.com/pha-pro-software/.

[76] Available at www.bakerrisk.com/products/software-tools/pha-tool.

[77] Available at www.primatech.com/software/phaworks.

Table A.2.
Software tools for event tree analysis/fault tree analysis

Name	*CAFTA*[78]	*ITEM ToolKit*[79]	*Reliability Workbench / FaultTree+*[80]	*RAM Commander*[81]	*RiskSpectrum*[82]
Developer	EPRI	ITEM Software	Isograph	ALD Software Limited	Lloyd's Register
Purpose	FTA, ETA	FTA, ETA, FMEA/FMECA	FTA, ETA, FMEA/FMECA	FTA, ETA, FMECA	FTA, ETA
Use	Generic analysis of fault trees and event trees		Fault tree and linked event tree modelling and analysis	Evaluation of electronic/ mechanical system reliability	Fault tree and linked event tree modelling and analysis
Benefits	Simplifies accident consequence modelling using event trees. Easy integration of fault trees, event trees and reliability database	Determines element importance; integration with other modules addressing reliability and system costing	Integrated failure data libraries. Can link to other modules addressing reliability	Detailed equipment/system level analysis; sensitivity analysis	Can link to other modules addressing risk components, including human reliability analysis Can address internal, area (fire and flooding) and external (seismic) events
Site-specific conditions can be incorporated	Yes				Yes
Limitations	Software access limited to EPRI members	Reliability data must be customized by user		Aligned with aerospace, defence, transportation industry standards	Proprietary computational algorithm. Focus on nuclear industry
Availability	Licensed; Demonstration version available without ability to save files	Licensed; Demonstration version available without ability to save files	Licensed	Licensed	Licensed

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[78] Available at www.epri.com/research/products/000000003002004316.
[79] Available at www.itemsoft.com/item_toolkit.html.
[80] Available at www.isograph.com/software/reliability-workbench/fault-tree-analysis-software/.
[81] Available at https://aldservice.com/reliability-products/rams-software.html.
[82] Available at www.lr.org/en/riskspectrum/technical-information/psa/.

Name	*CAFTA*[78]	*ITEM ToolKit*[79]	*Reliability Workbench / FaultTree+*[80]	*RAM Commander*[81]	*RiskSpectrum*[82]
		and session limit			

Abbreviations: EPRI, Electric Power Research Institute.

III. Software tools for quantitative risk analysis

Table A.3 contains a sample of commercially available quantitative risk analysis software.

Table A.3.
Software tools for quantitative risk analysis

Name	*ARIPAR*[83]	*FLACS-RISKCURVES*[84]	*QRATool*[85]	*RAPID-N*[86]	*Safeti*[87]	*SHEPHERD*[88]
Developer	JRC	TNO (Owner: GexCon)	BakerRisk	JRC	DNV	Shell (Owner: GexCon)
Description	Performs quantitative area risk assessment, evaluating risk resulting from major hazardous substance accidents	Quantifies the risks of storage and transport of hazardous substances to the surrounding population and structures, both in the urban environment and at chemical facilities	Aggregates consequences from SafeSite software and applies frequency information	Addresses Natech at critical chemical infrastructure	Quantitative risk analysis of onshore process, chemical and petrochemical facilities	Risk management software tailored for onshore facilities and operations
Purpose	General	General	General	Natech	General	Onshore oil/gas
Use	Risk contours and f-n curves	Evaluation of high-risk activities /scenarios, urban planning, regulatory and corporate criteria	Evaluation and ranking of explosion, fire, and toxic risks and mitigation strategies. Individual or societal risk results. Plot exceedance consequences	Addresses Natech involving releases of hazardous substances, fires, and explosions	Risk contours, f-n curves, and rankings of risk contributors. Accounts for local population and weather	Risk analysis

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[83] Available at https://publications.jrc.ec.europa.eu/repository/handle/JRC66551.
[84] Available at https://gexcon.com/products-services/riskcurves-software/.
[85] Available at www.bakerrisk.com/products/software-tools/qratool/.
[86] Rapid NaTech Risk Assessment Tool (RAPID-N) available at https://rapidn.jrc.ec.europa.eu/.
[87] Available at https://dnv.com/safeti.
[88] Available at https://gexcon.com/products-services/shell-shepherd-software/.

Name	*ARIPAR*[83]	*FLACS-RISKCURVES*[84]	*QRATool*[85]	*RAPID-N*[86]	*Safeti*[87]	*SHEPHERD*[88]
Addresses chemical transport risk	Yes	Yes	No	No	Yes	Yes
Benefits	Area risk control based on geographical information system platform	Open architecture allowing inputs from different software	Risk results in multiple options for individual or societal risk	Only known tool on Natech	Chemical library included	
Quick results	Yes				Yes	
Threat zones can be plotted on maps	Yes		Yes		Yes	Yes
Sensitivity analysis	Yes					Yes
Verification and validation publicly available	Yes	Yes (in Yellow Book)		Yes		
Can incorporate site-specific conditions	Yes		Yes		Yes	Yes
Limitations	Physical models not described	Complex data input required	Relies on consequence analysis from SafeSite with no other import available	Uses EPA RMP Guidance for Off-site Consequence Analysis input	Integral models	No modelling of toxic releases
Does not model environmental consequences	X		X	X	X	X
Verification and validation not publicly available			X		X	X
Availability	Discontinued	Licensed	Licensed	Free with waiver	Licensed	Licensed

Abbreviations: EPA, United States Environmental Protection Agency; RMP, Risk Management Programme.

IV. Software tools for consequence analysis

Table A.4 contains a sample of commercially available consequence analysis software.

Table A.4.
Software tools for consequence analysis

Name	*ADAM*[89]	*ALOHA*[90]	*BREEZE*[91]	*CANARY*[92]	*DEGADIS*[93]
Developer	JRC	EPA	Trinity Consultants	Quest Consultants	EPA
Description	Calculates the physical effects of industrial accidents resulting from an unintended release of a hazardous substance, chemical fires, blast effects of VCE, and inhalation of toxic chemical vapours	Models chemical releases for emergency responders and planners. Estimates toxic cloud dispersion after a chemical release and several fire and explosion scenarios	Multi-module air dispersion modelling platform; models fire, explosion, air toxics, human health, and environmental impacts. Based on EPA-developed software (AERMOD)	Consequence and hazard modelling tool that provides thermodynamic calculations for time-varying fluid releases	Models transport of toxic chemical releases into atmosphere
Use	CA of flammable and toxic releases	CA of flammable and toxic releases	Modelling of various consequence scenarios	CA of flammable releases and loss of containment scenarios	Dispersion of toxic releases (continuous, instantaneous, finite duration or time-variant)
Source Terms[94]	Yes	Manual	Yes	Yes	Manual
Physical Effects[95]	All	Dispersion	All	All	Dispersion
Vulnerability[96]	Yes	Yes	Yes	Yes	Exposure intensity
Benefits	Easy to use for European Union	Produces reasonable results quickly	Can model non-steady-state releases;	Chemical database. Hazard models for vapor	Models variety of dense gas

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[89] Accident Damage Analysis Module (ADAM) available at https://adam.jrc.ec.europa.eu/en/adam/content.
[90] Areal Locations of Hazardous Atmospheres (ALOHA) available at https://epa.gov/cameo/aloha-software.
[91] Available at www.trinityconsultants.com/software.
[92] Available at www.questconsult.com/software/canary/.
[93] Dense Gas Dispersion Model (DEGADIS) available at https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=&direntryid=2904.
[94] Amount of chemical released in a loss of containment event, including relevant chemical parameters
[95] Toxic gas dispersion, fire thermal radiation, explosion overpressure, etc.
[96] Harm produced by physical effects, accounting for likelihood, duration, intensity of exposure

Name	*ADAM*[89]	*ALOHA*[90]	*BREEZE*[91]	*CANARY*[92]	*DEGADIS*[93]
	competent authorities, designed with intent to include European Union regulations and directives in consequence modelling	enough for emergency responder use. Can link to live conditions in United States. Easy to use in the field	Modules for LNG/LPG; Enhanced visualization and data export manipulation tools	dispersion, fire radiation or VCE can be evaluated against gas concentration, radiant flux, or overpressure consequence endpoints.	release conditions
Limitations	Software cannot be extended to non-governmental organisations.	Some models simplified for ease of use and speed of results	ExDAM not appropriate for time-variant pressure/ impulse profiles or for congested spaces	No known limitations.	Only one set of meteorological conditions can be simulated. Limited to dense gases
Availability	Free[97]	Free	Licensed[98]	Licensed	Free

Name	*exploCFD*[99]	*FLACS-CFD*[100]	*FLACS-EFFECTS*[101]	*Fluidyn*[102]	*FRED*[103]
Developer	Advanced Analysis Australia	GexCon	TNO (Owner: GexCon)	Fluidyn	Shell (Owner: GexCon)
Description	Specific to explosion effects. Detailed models available for BLEVE, high explosives and dust clouds	3-dimensional CFD modelling for flammable and toxic releases. Incorporates contributing and mitigating effects, including confinement and congestions due to real geometry,	Models behaviour of toxic or flammable gases, liquefied gases, and liquids from moment of release to resulting physical effects	CFD modelling platform with multiple modules for specific scenarios	Consequence modelling tool underpinned by advanced thermodynamic model which enables extended multi-component fuel representation to be used in nearly all models

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[97] Reserved to European Union competent authorities, European Union countries' neighbours and Organisation for Economic Co-operation and Development countries with chemical risk management responsibilities. Not available to non-governmental organizations (NGOs) (industry, external consultants, etc.).

[98] AERMOD available through United States Environmental Protection Agency for free at www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod.

[99] Available at www.advanalysis.com/explocfd.

[100] Available at https://gexcon.com/products-services/flacs-software/.

[101] Available at https://gexcon.com/products-services/effects-consequence-modelling-software/.

[102] Available at www.fluidyn.com/?page_id=96.

[103] Fire, Release, Explosion and Dispersion (FRED) available at https://gexcon.com/products-services/shell-fred-software/.

Name	*exploCFD*[99]	*FLACS-CFD*[100]	*FLACS-EFFECTS*[101]	*Fluidyn*[102]	*FRED*[103]
		ventilation, and deluge			
Use	Explosion modelling	CA for detailed 3-dimensional scenarios	CA of flammable and toxic releases	CFD models of flammable and toxic releases	CA of flammable releases
Source Terms	Yes	Yes (DIPPR)	Yes (DIPPR)	Manual	Yes (Thermodynamic model consisting of multi-component fuel)
Physical Effects	Explosion	All	All	All	All
Vulnerability	Fire, explosion effects	Explosion overpressure, fire radiation 3-dimensional effects	Doses due to dispersion, consequences to human life/lethality	Intensity of fire exposure, toxic gas exposure, explosion pressure contours	Fire, toxic release, and explosion effects
Benefits	Ease of use, no geometry construction required, allows modelling of TNT, ammonium nitrate, along with dust and gas explosions	Geometrical features are considered for fire, explosion, and toxic releases	Considers structural damage	PANFIRE module considers effects of active and passive protection systems VENTIL module considers confined space effects FLOWSOL module evaluates liquid-borne environmental effects including groundwater pollution	Developed and validated through extensive programme of large-scale experiments, substantial investment, joint industry projects and published scientific literature
Limitations	Limited to fire and explosion applications, no toxic dispersion modelling	Computationally expensive	Requires significant experience to validate models and result	No known limitations	No modelling of toxic releases. Focus on offshore industry
Availability	Licensed	Licensed	Licensed	Licensed	Licensed

Name	*KFX*[104]	*MET*[105]	*Phast*[106]	*SAFER One*[107]	*SafeSite 3G*[108]
Developer	DNV	ISi Technologie GmbH	DNV	SAFER SYSTEMS	BakerRisk
Description	CFD tools for simulation of dispersion, fires, and explosions in congested areas.	Assesses chemical accidents and estimates toxic, explosion, thermal radiation, and solid particulate release	Examines progress of a potential incident from initial release to far-field dispersion analysis, including modelling of pool spreading and evaporation, and flammable and toxic effects	Models a chemical release or combustion event in real time to facilitate emergency response tactics. Facility layout is superimposed on maps with live traffic and Internet weather integrated to provide real time situational snapshot	Simulates chemical discharge, dispersion, pool spread and volatilization, jet, and pool fires, VCE, and vulnerability during fire, toxic and explosion events
Use	CA for fire and explosion scenarios in congested areas	CA of flammable and toxic releases and highly active substances	CA of flammable and toxic releases	Real-time emergency response and communication across organization	CA of multiple scenario types
Source Terms	Yes	Manual	Yes	Manual	Manual
Physical Effects	Fire, Dispersion	All	All	Dispersion	All
Vulnerability	Yes	Yes	Yes	Yes	Yes
Benefits	Can account for congested areas, weather effects, and fire mitigation with water systems. Addresses a wide range of liquid and gas	Chemical incompatibility screening. Quick results	Applicable to design and operation applications. Widely adopted and considered industry standard	Real-time simulation; integrates with chemical gas and weather sensors; cloud-based	Discharge, dispersion, and blast modelling techniques validated by historical data and testing performed by developer. Can be used for transport routes

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[104] Kameleon FireEx (KFX) available at www.dnv.com/services/fire-simulation-software-cfd-simulation-kameleon-fireex-kfx-110598.
[105] Models for Effects with Toxic and flammable gases (MET) available at www.isitech.com/met-fuer-windows.html.
[106] Available at https://dnv.com/phast.
[107] Available at https://safersystem.com/products/safer-one/.
[108] Available at www.bakerrisk.com/products/software-tools/safesite/.

Name	*KFX*[104]	*MET*[105]	*Phast*[106]	*SAFER One*[107]	*SafeSite 3G*[108]
	leak and fire scenarios. Optimization of passive fire protection				
Limitations	Focus on petroleum industry		Various versions deal with multiple components. Some explosion models are simplified	Physical models unknown, no proactive/static modelling of releases	Focus on onshore industry. Complex user interface
Availability	Licensed	Licensed	Licensed	Licensed	Licensed

Abbreviations: BLEVE, boiling liquid expanding vapour explosion; CA, consequence analysis; CFD, computational fluid dynamics; DIPPR, Design Institute for Physical Properties; TNT, trinitrotoluene; VCE, vapour cloud explosion.

Risk Assessment for Industrial Accident Prevention

Risk assessments for industrial facilities are essential for the prevention of industrial accidents. The United Nations Economic Commission for Europe (UNECE) Convention on the Transboundary Effects of Industrial Accidents aims to help its Parties and committed countries to prevent, prepare for and respond to industrial accidents, especially ones that can have transboundary effects. It also fosters transboundary cooperation among its Parties and beyond. As risk assessment is enshrined in the Convention's provisions, UNECE held a seminar on risk assessment methodologies (Geneva, 4 December 2018) to support countries in implementing the relevant provisions. The seminar resulted in conclusions and recommendations on the challenges in executing transboundary risk assessment for industrial facilities and the need for more information exchange on risk assessment methodologies used in the UNECE region, including available software tools. The present report was developed on this basis.

The report, prepared under the auspices of the Convention, is divided into two parts. Part 1 provides a general overview of risk assessment methodologies applicable to risks arising from hazardous activities. It is not exhaustive but rather provides an overview of methods used in the UNECE region. Part 2 presents eighteen case studies submitted by countries from the UNECE region on risk assessment methodologies applied at industrial facilities and available software tools to support risk assessments. The case studies span five types of facilities: liquified natural gas/liquified petroleum gas storage tanks; ammonia refrigeration facilities; oil terminals; ammonium nitrate storage facilities; and chlorine facilities. Overall, the report is a resource for national authorities, policymakers, operators and anyone with interest to gain a deeper understanding of risk assessments for industrial facilities and to strengthen industrial accident prevention.

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