



Economic Commission for Europe**Conference of the Parties to the Convention on the
Transboundary Effects of Industrial Accidents****Twelfth meeting**

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Item 10 (a) of the provisional agenda

Facilitation of implementation:**(a) Risk assessment for industrial accident prevention****Risk assessment for industrial accident prevention: Overview
of risk assessment methods****Report submitted by the small group on risk assessment***Summary*

The Conference of the Parties, at its eleventh meeting (Geneva (hybrid), 7–9 December 2020), requested the small group on risk assessment to submit, for review at its twelfth meeting, two reports on risk assessment methodologies for chemical installations in the United Nations Economic Commission for Europe region: one providing an introduction to risk assessment methodologies for industrial accident prevention and available software tools and another one presenting specific case studies on risk assessment methodologies applied at selected industrial facilities in the United Nations Economic Commission for Europe region — also covering available software tools.^a

The present report was prepared by a contractor with regular guidance by the small group on risk assessment, the secretariat's support and financial support from Switzerland. It was also reviewed and supported by the Convention's Bureau and Working Group on Implementation. The report provides an overview of the risk assessment process, including risk analysis tools and risk evaluation criteria. It goes beyond listing risk assessment methods and tools, by presenting benefits and challenges of applying risk assessment methodologies in practice. It should be read in conjunction with the second report, which contains selected case studies on risk assessment methodologies applied in the United Nations Economic Commission for Europe region and lists some software tools available to support chemical installation risk assessment.

The Conference of the Parties is invited to:

- (a) Take note of the present report providing an overview of risk assessment methods (ECE/CP.TEIA/2022/8);
- (b) Also take note of the second report, containing case studies and some available software tools for chemical installation risk assessment (ECE/CP.TEIA/2022/9);
- (c) Consider the information in, and promote the use of, the two risk assessment reports in future work, including as supporting background material;



- (d) Request the secretariat to publish the reports on risk assessment in the three official United Nations Economic Commission for Europe working languages in the biennium 2023–2024.

^a ECE/CP.TEIA/42, para. 75.

I. Introduction, background and scope

1. The 1992 United Nations Economic Commission for Europe (ECE) 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 41 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 ECE 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 ECE region, but can also benefit States members of the United Nations beyond the region, in line with the communication, outreach and engagement strategies.

2. Risk assessment is an integral part of accident prevention, enshrined in the Convention's provisions (e.g., art. 6 and annex V). An ECE seminar on risk assessment methodologies (Geneva, 4 December 2018) sought to support ECE 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 ECE region, including available software tools. Accordingly, this report was prioritized among the seminar recommendations.

3. 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 ECE region.

4. 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 ECE 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

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

6. 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;

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

(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

(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.

7. 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

(f) “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

(g) “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;

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.

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.

- (h) “Risk identification” — Process of finding, recognizing, and describing risks;¹²
- (i) “What-if” — See subsection B.3.1.
8. 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
- (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;

¹² ISO, ISO Guide 73:2009(en).

¹³ Ibid.

¹⁴ CPPS, “CCPS Process Safety Glossary”, available at www.aisc.org/ccps/resources/glossary?page=1.

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).

(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

9. 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

(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

10. 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.

11. 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:

²² Ibid.

²³ CCPS, *Guidelines for Hazard*.

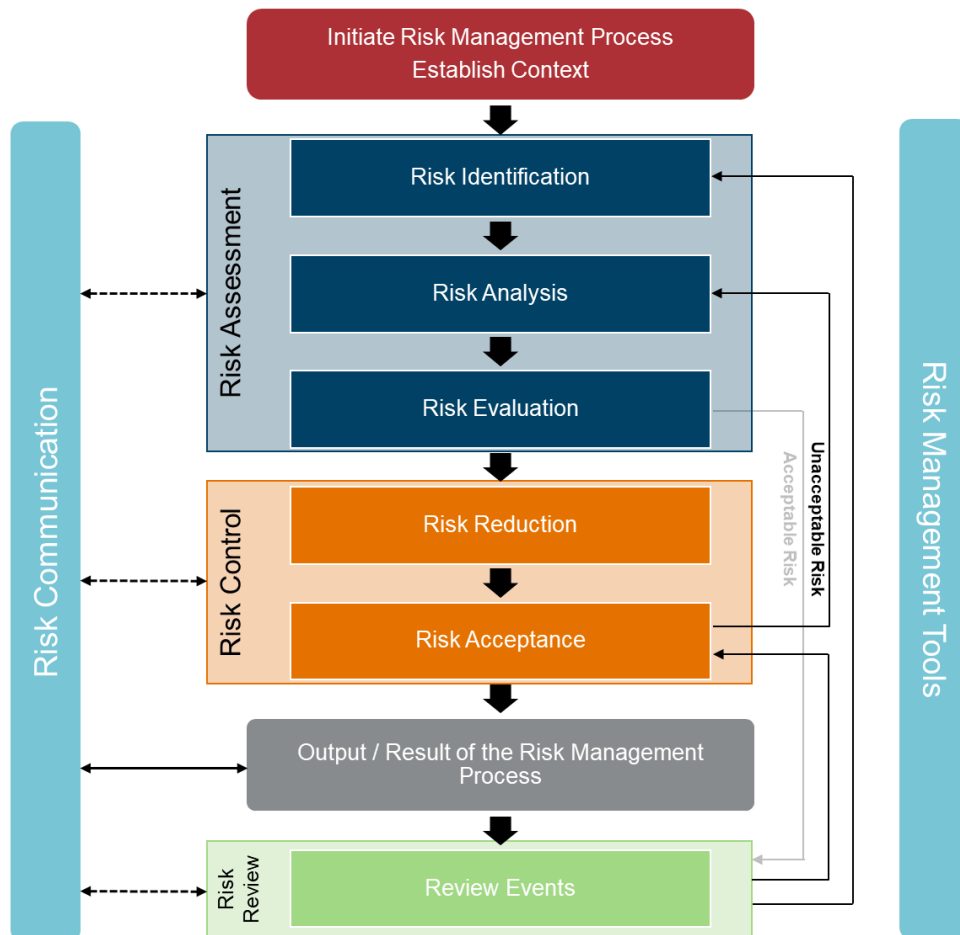
²⁴ CCPS, *Guidelines for Investigating Process Safety Incidents: Third Edition*, (New York, AIChE, 2019).

²⁵ ISO, ISO Guide 73:2009(en).

²⁶ Ibid.

- (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.

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 report²⁷ (see figure 1 and section B for clarification).

12. 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.

13. 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

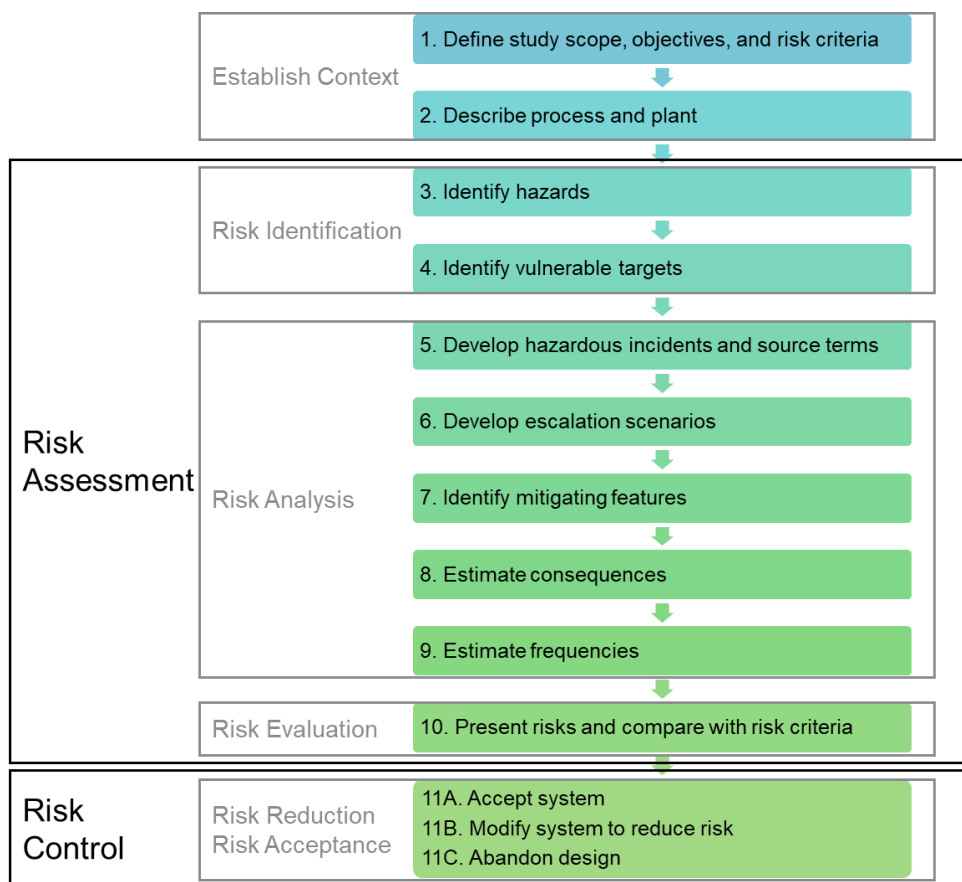
14. This report focuses on the first component of risk management: risk assessment. Broadly speaking, risk assessment encompasses control of hazardous processes; the scope of this document is limited to control of acute effects from catastrophic releases of hazardous substances (defined in Convention,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

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

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.

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

Figure 2
Risk assessment process



Source: Adapted from Sam Mannan, ed., *Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment, and Control — Fourth Edition* (n.p., Elsevier Incorporated, 2012).

16. 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

17. 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 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

18. 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

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

³⁰ Ibid.

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

19. 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

20. 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.

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.

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*.

1.2. Checklist

21. 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

22. 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

23. 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

24. 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

25. 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

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).

major effects (fire, explosion, toxic release) and damage to human health and the environment.

26. 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

27. 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.

28. 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

29. 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.

30. 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

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*.

consequences.⁴⁰ These methods can therefore capture the probability of many scenarios leading to undesirable outcomes.

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

2.1. *Qualitative methods*

32. 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*

33. 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*

34. 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**

35. 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*

36. 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

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*.

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

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 Mannan, *Lees' Loss*.

3.2. Hazard and Operability

37. 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

38. 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.

⁴² CCPS, *Guidelines for Hazard*.

⁴³ P. K. Marhavidas, 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.

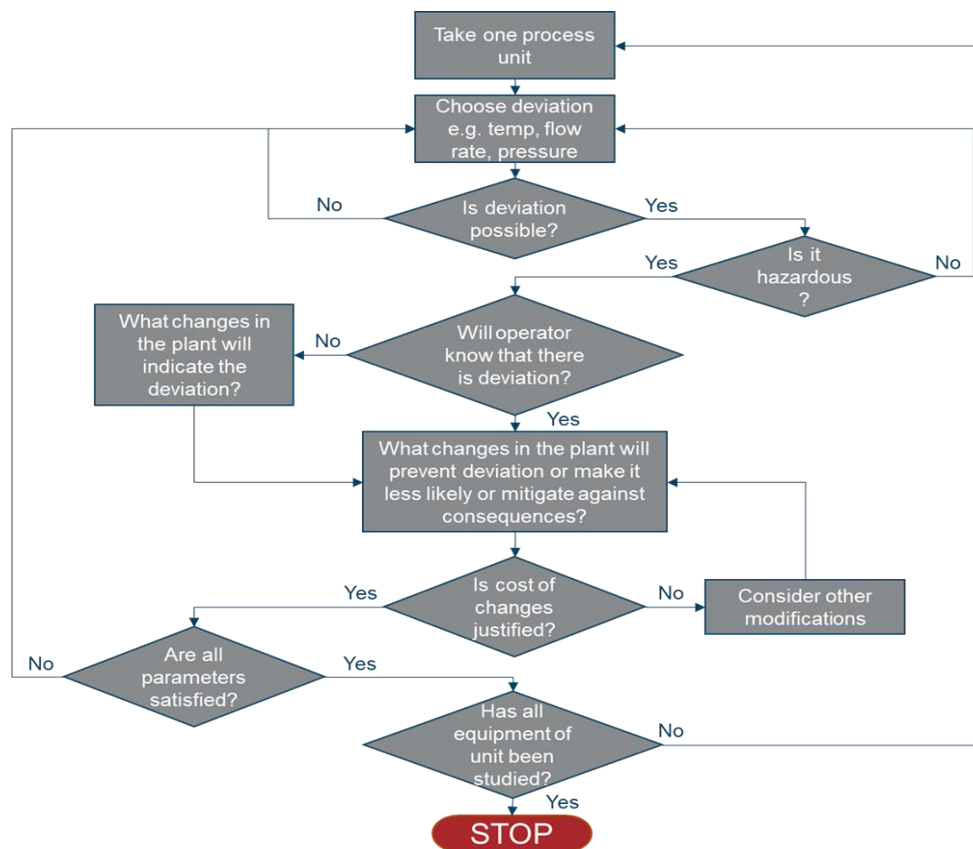
⁴⁴ Faisal I. Khan and S. A. Abbasi, "OptHAZOP – an effective and optimum approach for HAZOP study", *Journal of Loss Prevention in the Process Industries*, vol. 10, No. 3 (May 1997), pp. 191–204.

Table 3
Hazard and Operability workshop guidewords for scenario development

<i>Guide Word</i>	<i>Meaning</i>	<i>Parameter</i>	<i>Deviation</i>
None	Negation intention	Flow Level	No flow Zero level
Less	Quantitative decrease	Flow Level Temperature Pressure Concentration	Low flow rate Low level Low temperature Low pressure Low concentration
More	Quantitative increase	Flow Level Temperature Pressure Concentration	High flow rate High level High temperature High pressure High concentration
Reverse	Logical opposite	Flow Pressure	Reverse flow rate Reverse pressure
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*, vol. 11, No. 4 (July 1998), pp. 261–277.

Figure 3
Hazard and Operability process stream



Source: Khan, "OptHAZOP".

39. 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

40. 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.

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).

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; reseal 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: Mannan, *Lees' Loss*.

41. 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

42. 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.

43. 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.

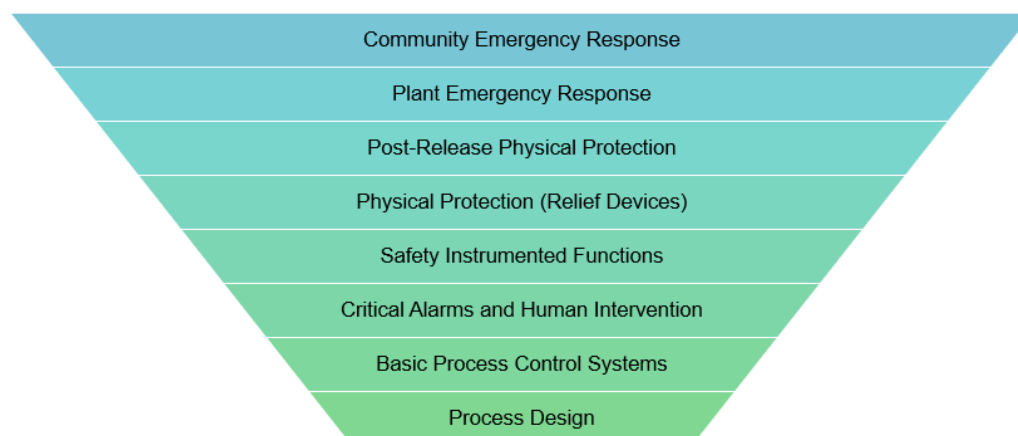
3.5. Layers of Protection Analysis

44. 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.

⁴⁷ Mannan, *Lees' Loss*.

⁴⁸ CCPS, *Guidelines for Hazard*.

Figure 4
Independent protection layers against a possible accident



Source: CCPS, *Layer of Protection Analysis: Simplified Process Risk Assessment* (New York, AIChE, 2001).

45. LOPA is a scenario-based risk analysis method following the steps below:
- Identify a target consequence, determine possible scenarios, and select an incident scenario;
 - Identify the cause of the selected scenario and determine its frequency;
 - Define the independent protection layers and estimate their failure frequencies;
 - Calculate the overall frequency of the scenario by combining cause and independent protection layer failures;
 - Determine risk level for the scenario by identifying magnitude of the consequence and continue with risk evaluation.

46. 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)

47. 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 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.

48. 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

⁴⁹ CCPS, *Guidelines for Hazard*.

⁵⁰ Ibid.

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*

49. 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).

50. 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).

51. 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.

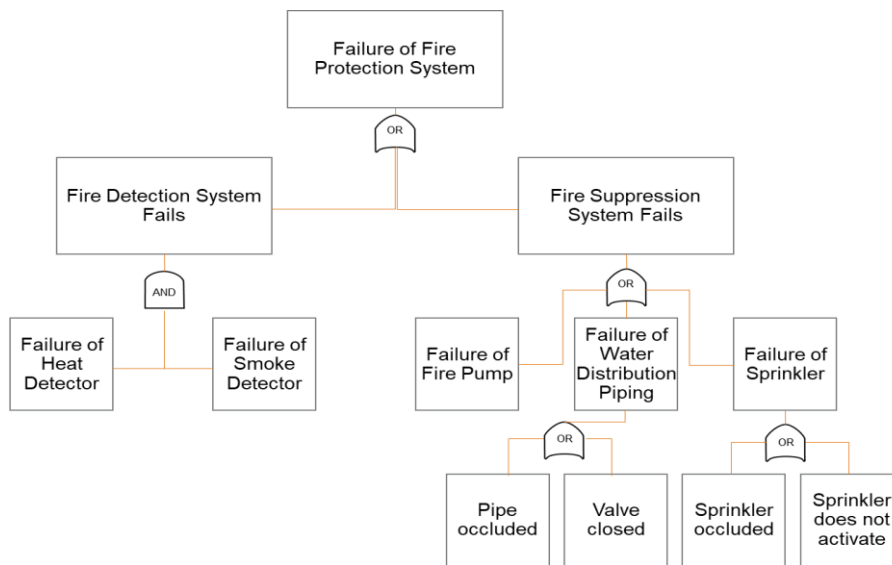
52. A weakness of FTA is that failure frequency and on-demand probability data for system components and events can have associated uncertainty, and may not be readily available, particularly if the system or component is new and lacks an established operational history. In such cases, these data may 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.

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

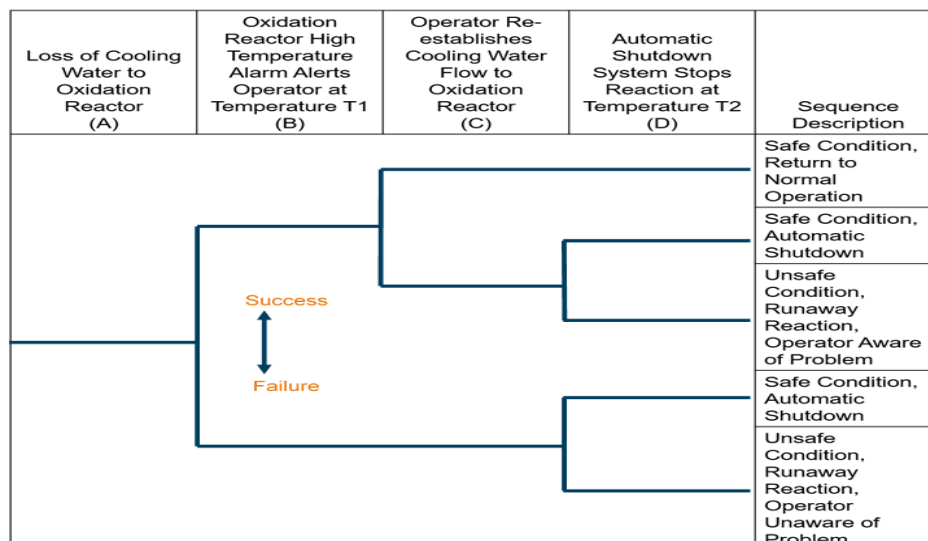


Source: Created by author of present report.

3.8. *Event Tree Analysis*

53. 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).

Figure 6
Event tree for the example initiating cause “loss of cooling water to the oxidation reactor”



Source: CCPS, *Guidelines for hazard*.

54. 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

⁵⁴ Marhavilas “Risk Analysis”.

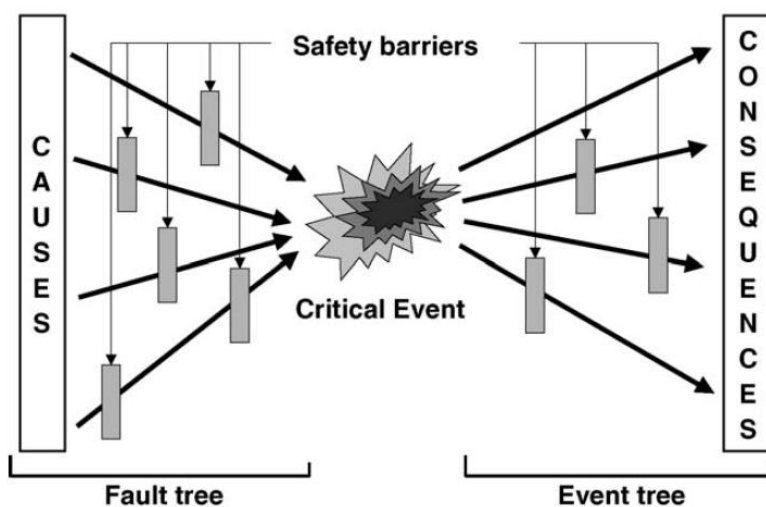
methods are often linked in that FTA considers the likelihood of the initiating event occurring and ETA considers the likelihood of one or more consequences given that the initiating event occurs. Accordingly, FTA considers and accounts for prevention measures and ETA considers and accounts for mitigation 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.

3.9. Bow-tie model

55. 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.

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*, vol. 130, No. 3 (March, 2006), pp. 220–233.

56. 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.

4. Important considerations in selecting risk analysis tools

57. 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.

58. 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

<i>Method/tool</i>	<i>Advantages</i>	<i>Challenges</i>	<i>Applicable risk assessment steps (see figure 2Error! Reference source not found.)</i>
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
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 identification: 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/FM ECA	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

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

Sources: CCPS, Guidelines for Hazard; Mannan, Lees' Loss; and Peeters, "Improving failure analysis".

2.6. Results of risk analysis step

59. 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

60. 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

61. 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

62. 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.

63. 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.

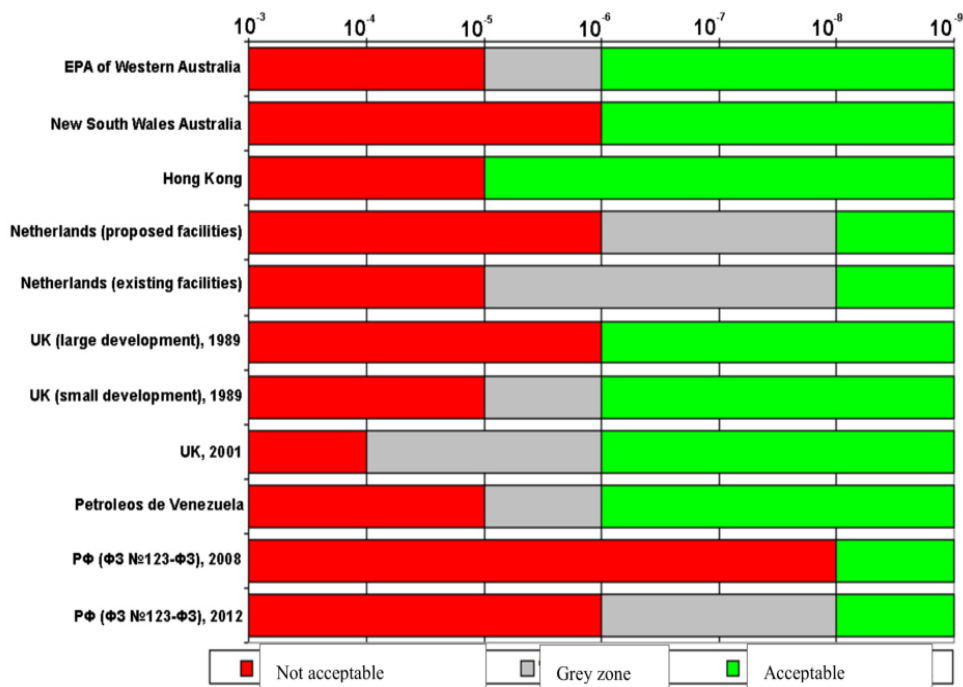
1.2. Individual risk criteria

64. 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.

65. 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

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, ECE seminar on risk assessment methodologies (Geneva, 4 December 2018).

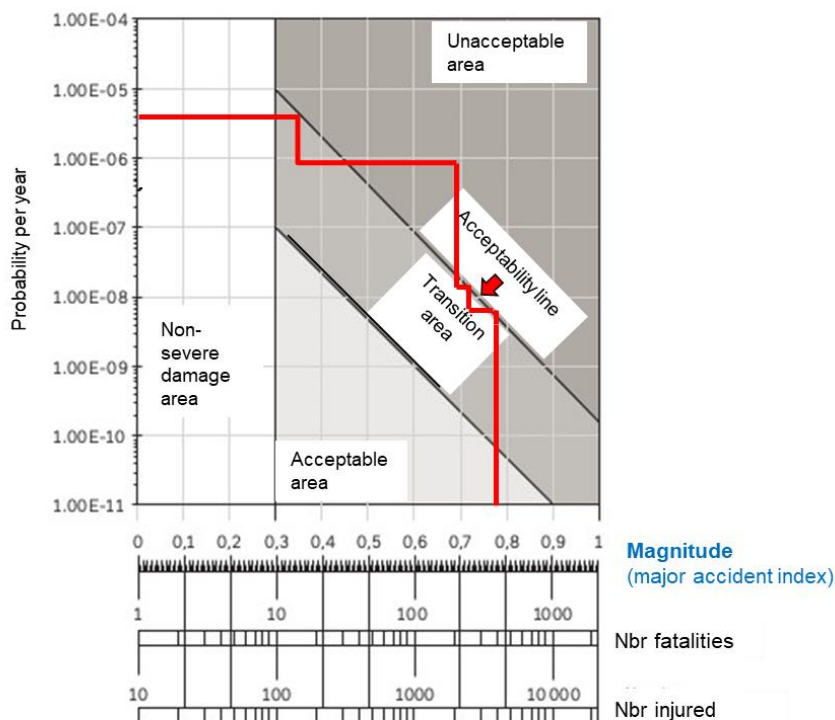
Abbreviations: EPA, Environmental Protection Agency; Hong Kong, Hong Kong, China; UK, United Kingdom.

1.3. Societal risk criteria

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

⁵⁵ Martin Merkofer, “Risk Assessment Seminar: Scope, cases selection, effect and risk assessment methodologies”, presentation given at seminar on risk assessment methodologies, 4 December 2018, Geneva.

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



Source: Michael Hösli and others, Beurteilungskriterien zur Störfallverordnung (Bern, Federal Office for the Environment, 2018).

Abbreviations: Nbr, number.

2. As Low as Reasonably Practicable/Achievable

67. 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

68. 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.

69. 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,

⁵⁶ CCPS, *Guidelines for Developing Quantitative*.

minimum dollars to reach “acceptable risk” or “gross disproportionality” to the risk reduction.

70. 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.

71. 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

V. Benefits and challenges of risk assessments

A. Benefits of risk assessment and applying risk assessment methodology

1. Transboundary considerations

72. 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

73. 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.

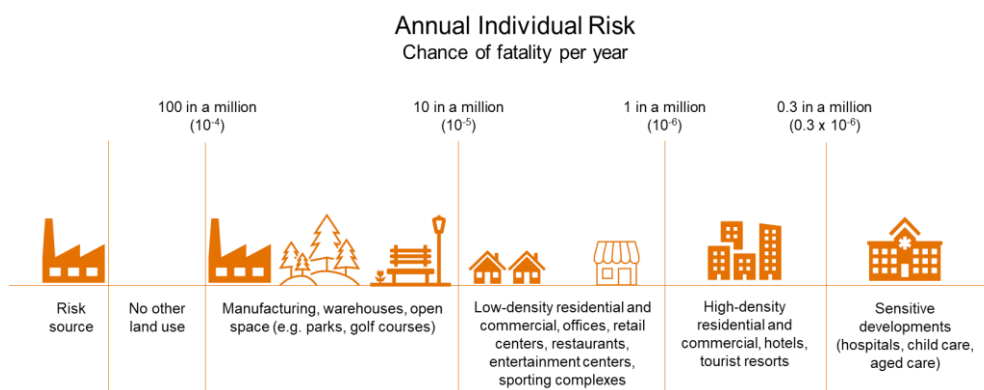
74. Risk assessments can support land-use planning by overlaying broad order-of-magnitude risk contours onto land-use type (see figure 10). Industry guidance is available for this specific application through several organizations.⁵⁹ By comparing outputs from risk assessments to characteristics of potential 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.

⁵⁷ Health and Safety Executive, “Appraisal values or ‘unit costs’”, available at www.hse.gov.uk/economics/eauappraisal.htm.

⁵⁸ Merkofer, “Risk Assessment Seminar”.

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

Figure 10
Allowable land and uses



Sources: MIACC, Risk-based.

75. 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

76. 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 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

77. 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

78. 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

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).

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.

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

79. 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: inherent limitations of risk analysis methods

1. Inherent limitations of risk analysis methods

80. 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;

(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

81. 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.

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).

3. Education, experience and expertise

82. 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

83. 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).

84. 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.

85. 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

86. 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.

6. Limitations in knowledge of and access to software

87. 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 ECE 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

88. 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,

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).

compared to other countries with more advanced technology that incorporates these additional safety measures within their higher baseline.

VI. Conclusions

89. 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 ECE 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).

90. Part 2 describes case studies where risk assessment methods were applied to ECE 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.
