Chemical Process Quantitative Risk Analysis

7.1. Overview

7.1.1. Introduction

The concept of risk is not new, and has always been a feature of our daily life and activities. Risk is everywhere around us. Most people are probably aware that there is risk involved in being on the roads, whether as a motorist or pedestrian, and that every day people are killed in accidents. Most people who live in areas close to hurricane-prone coasts realize that they risk losing their lives as well as their homes. Nevertheless, most people accept these or similar potential risks. This may be due to lack of awareness of the real potential. They may believe, having only speculation and anecdotal history as guides, that nothing adverse will happen to them. Alternatively, this may reflect a willingness to accept a higher level of risk when there is a perceived benefit in doing so.

A number of major industries pose potential hazards to those who work in or near them. These vary from coal mining and quarrying, to modern travel and the nuclear industry. Some of these industries can have high potential for extensive loss of life in a single incident. In order to assist in risk evaluation and control, quantitative risk analysis has been developed to provide logically derived information that can be used directly to support decision making. The nuclear industry, which dates back to the mid 1940s, was one of the leaders in using this approach. Risk management started in the 1960s in the process industries. In the chemical process industry (CPI) this approach is known as Chemical Process Quantitative Risk Analysis (CPQRA).

This chapter reviews the type and extent of the documentation needed to support this type of analysis.
7.1.2. Goals and Benefits

Both the goals and benefits of the application of CPQRA within the CPI flow from the basic definition of the phenomenon known as risk.

One definition of risk is the potential of an activity or operation to cause harm (e.g., death, injury, damage, or pollution). Conceptually, risk ($R$) is often represented as the product of the consequence ($C$) of an incident and probability of occurrence ($P$):

$$ R = C \times P $$

The number of injuries, fatal or nonfatal, is commonly used to characterize severity or consequence of the incident; although, the overall cost of damage can also be used. The frequency of the incident can be used to represent probability of occurrence. Risk can be:

- voluntary, where the participant willingly and knowingly undertakes the high-risk activity, such as:
  - recreational adventures (e.g., SCUBA diving or rock climbing) or
  - occupational risk, where people work in a job or location where they have a vested interest (e.g., remuneration via wages or salaries);
- involuntary, where the person involved has little or no choice and no benefits in undergoing the risks, such as:
  - natural disasters; or
  - where toxic releases, fires, and/or explosions, may endanger those in close proximity.

Risk can be quantified, but special expertise may be required. CCPS has published a book *Guidelines for Chemical Process Quantitative Risk Analysis* as a resource document on how to conduct a CPQRA. Some engineering and construction firms and some major organizations in the process industry employ reliability engineers and/or risk analysts to assist in preparing these assessments. Where such expertise is required but not available, organizations may seek assistance from qualified consultants.

The goals of applying CPQRA within the CPI are:

- to identify and quantify, insofar as possible, the key factors that contribute to the total risk related to using a particular chemical process, or a facility incorporating that process; and
- to systematically evaluate and analyze this data so that the risk can be reduced, managed, or negated by intelligent choices of design, construction, operation, and control aspects of the specific processes or facilities involved.

The benefits achieved from CPQRA are derived from the ability to objectively evaluate all types of risk (e.g., environmental, economic, and exposures of humans to hazards). For example, the ability to evaluate risk permits the selection of cost-effective risk reduction measures for existing facilities. Further, it permits
assessing the feasibility of applying new chemical processes before significant amounts of financial and human resources are invested in new facilities.

7.2. Description of CPQRA

7.2.1. Objectives

There can be many reasons for performing a CPQRA. Some of these are addressed in the following paragraphs.

Layout or Siting. Traditionally, the layout of a plant site has been determined using experience and judgment to establish interplant and interunit separation distances, as well as distances to centers of employee concentration like control rooms, workshops, and offices. Some organizations have established historically based guideline tables of minimum acceptable separation distances. However, some organizations and some authorities consider the guideline approach as inadequate, and they require more extensive quantification of the actual risks involved. A CPQRA can address factors such as overpressure, thermal radiation, or toxic effects when estimating the risks associated with proposed facility layouts, permitting a quantitative approach to the selection of alternatives.

Community Impact. The close proximity of a community to a high hazard installation can pose problems that are best resolved before construction. Subsequent correction may be difficult or impossible without shutdown or elimination of the activity. CPQRA provides a mechanism for evaluating the risk posed by a facility to the surrounding communities. CPQRA may also be used in emergency planning to establish priorities or to determine credible impact zones.

Comparison of Risk Reduction Alternatives. One of the common uses of CPQRA is for the comparison of risk reduction alternatives, to identify the lowest risk alternative where there are several possible designs, layouts, or processes. In this comparative mode, CPQRA simplifies the decision making, since:

- no comparison needs to be made with absolute standards or criteria, so this complex issue does not enter into the arguments, at least at this stage;
- comparisons can be limited to the areas of divergence between the alternatives (of considerable benefit in shortening an involved procedure, and reducing the necessary documentation);
- some of the assumptions that are made may be common for all of the alternatives, thus it is not critical that these assumptions be extensively researched to provide statistically high levels of confidence; reasonable data can be used, knowing that it may no longer be a critical item; and
- organizations that perform CPQRA find that the more limited comparative CPQRAs facilitate decision making by identifying the lowest risk alternative, withoutclouding the issues with intricate details.
**Regulatory Requirements.** CPQRA can be required to achieve regulatory compliance. There are few instances where CPQRA regulatory requirements currently exist in the United States; however, they are more common in some western European countries.

### 7.2.2. Performance of CPQRA

CPQRA cannot be simply described with a listing of its various analysis techniques, as can be done for PHA (Chapter 6) or Human Factors Analysis (Chapter 9). Many different approaches exist for estimating the frequency of occurrence for an undesired event. Similarly, there are a variety of ways in which the consequences of an event can be manifested, such as fires, explosions, and toxic gas exposures. For each of these types of event, there exists a multitude of ways to model, or estimate, the magnitude of the consequences. Reference should be made to the CCPS books and other publications listed in Section 7.6 for detailed descriptions of the various elements and tools that comprise CPQRA.

### 7.3. CPQRA Documentation

#### 7.3.1. CPQRA Program Documentation

Organizations wishing to implement CPQRA should include in their PSM program documentation guidance on the goals of CPQRA as well as procedures outlining how it is to be implemented. The PSM program documentation may include statements relevant to CPQRA including:

- who (by function) is to be responsible and accountable for any needed CPQRA;
- the practices to be followed in deciding if CPQRA is to be performed;
- the organization of the CPQRA itself, including selection of study scope, team, analysts, and methodology;
- criteria to be used for assessing CPQRA results;
- form of reporting the CPQRA results;
- resolution of recommendations resulting from the study;
- auditing the implementation and documentation of CPQRA; and
- auditing of the organization's CPQRA program, itself.

Further elaboration of some of these topics is provided below:

**CPQRA Analysts.** Considerable training and experience is required to properly perform some of the more sophisticated methodologies used in CPQRA. Some organizations may find it helpful to establish and document minimum qualification requirements for CPQRA analysts.
Scope. Performance of CPQRA can be time consuming and, therefore, expensive. The corporate PSM program documentation may contain guidance to assist in identifying those situations warranting CPQRA.

Methodology. As mentioned previously, there exists a multiplicity of CPQRA modeling methodologies, many requiring the use of sophisticated computer programs for their effective use. Some organizations may find it appropriate to standardize upon, and support, a limited subset of these methodologies. Appropriate guidance might be included in the CPQRA program documentation.

Criteria for Acceptance. The CPQRA program may document tolerable levels of risk for the various categories and types of risk (e.g., on-site, off-site, individual, or societal).

CPQRA Report. The CPQRA program documentation should identify key pieces of information that should be documented in the CPQRA report. One such list is given in Section 7.3.2, another example is given in APPENDIX C of the CCPS book Guidelines for Chemical Process Quantitative Risk Analysis.

Resolution of Recommendations. As in other elements of the PSM program, there should be a documented requirement for the prompt resolution of recommendations, including requirements for the assignment of specific responsibilities and accountabilities.

Auditing. The procedures for auditing CPQRA documentation should be documented.

7.3.2. Documentation of CPQRA Results

CPQRAs will vary considerably in scopes and objectives; consequently the type and style of documentation is likely to vary from one study to another. However, there are certain aspects of a CPQRA that should be carefully and clearly documented in order to provide adequate transparency; i.e., the ability of a reader to see and understand how the CPQRA was performed.

It is important in preparing the final report to remember who the potential readers may be. Some potential readers include:

- senior corporate officials;
- federal, state, or local government officials;
- consultants, including experts in CPQRA;
- other plant personnel; and
- the public.

Sometimes organizations perform CPQRA for internal purposes, and only their own management personnel are expected to see the report. Alternatively, CPQRAs may be called for by federal, state, or local government regulatory agencies, in which case the reports will be in the public arena for inspection. Since confidential internal documents sometimes become public (especially after inci-
dents), the writer should remember who the potential readership may be. A less technical summary, in addition to the executive summary, may then be appropriate.

The various aspects of the documentation that should be considered for inclusion in the CPQRA report are, by section name and content:

- **Table of Contents**, to include also a list of Appendixes.
- **Executive Summary**, to summarize the conclusions of the CPQRA, which should be given in lay language since some readers may be unfamiliar with CPQRA and its jargon;
- **Objective**, to state why the CPQRA was performed, and the objectives or goals to be met;
- **Scope**, to state what parts of a facility were included and explicitly what parts are not. Alternatively scope could be limited to hazards of a particular type (e.g., those due to flammable or toxic materials);
- **Definitions** (especially, for any potentially unfamiliar terms or terms whose use differs from their usual definition)
- **System Description**, to describe the process, the facility, and the equipment studied;
- **Hazard Scenario Identification**, to include:
  - listing of all hazard scenarios identified (with their likelihood to be considered later in Probability Assessment); and
  - statement of methods used to identify and develop scenarios and the reasons for those selected (see Chapter 6, Process Hazard Analysis).
- **Incident Consolidation**, to give an indication of which events and probabilities have been consolidated to produce a cumulative total probability (e.g., often a series of simple incidents like pipe flange leakages can be grouped to reduce the complexity of the modeling);
- **Selection of CPQRA Models**, to document the rationale used for selecting particular methods to mathematically model different aspects of the CPQRA;
- **Consequence/Impact Assessment**, to document how the selected models produce results that quantify the consequences of an incident, and how people and/or property are likely to be impacted;
- **Probability/Frequency Assessment**, to document how the probability of the incident is determined, to include:
  - source of the data bases for equipment failure or human error and frequency;
  - any critical assumptions made; and
  - any adjustments or departures from the referenced data bases and their justification
- **Risk Assessment**, to document the calculation of risk and the presentation of the basic results (bringing together Consequence/Impact and Probability/Frequency assessments);
- **Risk Analysis**, to document the derivation/selection of sets of values for risk, their meaning, and how they are to be compared with criteria/targets, or with other facilities, and to ensure that:
—realistic comparisons are made;
—effects of uncertainties, or confidence limits, are addressed; and
—conclusions drawn are the best ones, in terms of accuracy or reliability, which the models will support.

- **Recommendations for Risk Mitigation**, to recommend ways of addressing risk, if the assessed risk value was uncertain or not tolerable; and
- **Appendixes**, to ensure that the report itself is concise and not excessively interrupted by technical detail.

Appendixes can be very helpful in organizing that data presented in the report. The subject matter for each appendix should be kept separate, and appendixes should be included in a logical order. An Appendix index and/or a table of contents would be advisable, in addition to cross referencing in the text. Some examples of documentation that can be placed in appendixes are as follows:

- population statistics (demography);
- meteorological statistics (stability, wind speed and direction);
- relevant historical accidents (plant and worldwide);
- tabulations of comparable risks;
- equipment failure rate data base;
- human errors data base;
- physical property data;
- toxicological data;
- graphical results (e.g., F–N curves and Iso-risk contours);
- references cited;
- diagrammatic results (e.g. FTA); and
- maps and drawings.

This may not be a complete list, and some items may not be relevant to a particular CPQRA. Alternatively, some organizations may choose to document the more voluminous parts of this information, not in appendixes to a report, but as a separate report with a limited distribution.

The CPQRA documentation needs to be thorough, clear, and concise. Proper documentation helps to prevent guesswork on the part of the reader as well as to provide the full basis for the assessment, which can be invaluable for any future updates. Refer to Appendixes 7A through 7C for additional guidance on documentation of CPQRA.

### 7.3.3. Resolution of CPQRA Recommendations

It is common, as a result of a CPQRA, to formulate recommendations intended to reduce the risk of operating a process or facility. It is important to promptly and fully resolve each recommendation, just as was the case for PHA recommendations in Chapter 6. Reference should be made to Section 6.3.3 for a discussion of documentation of recommendations and their resolution.
7.4. Records Management

The records management task for CPQRA is quite similar to that for PHA. Indeed, there is considerable overlap in that much of the activity involved in hazard identification, scenario development, and frequency estimation for CPQRA is actually PHA using the techniques described in Chapter 6. Since there are no records management issues unique to CPQRA, reference is made to Section 6.4 and Chapter 4 for general guidance.

7.5. Auditing

An audit of CPQRA should first verify that a documented program for implementing CPQRA exists. This program would include elements outlined in Section 7.3.1 and records management practices referenced in Section 7.4 that are pertinent to the needs of the organization or facility.

The audit should next verify that the results of implementing CPQRA have been documented in the manner prescribed by the program. Particular emphasis should be placed upon the documentation of the resolution of recommendations.

Any deficiencies identified during the audit must be documented and resolved in a timely manner. It should be remembered when auditing, that the intent is not to confirm the technical accuracy or adequacy of the contents of the documentation but, rather, to confirm that the documentation practices conform to the established program. Auditing may, however, reveal areas of potential improvement in the implementation or the documentation of the CPQRA program, itself.

7.6. References

In addition to the references in this section, see those listed in Appendixes 7A, 7B, and 7C.

AIChe-CCPS, Guidelines for Chemical Process Quantitative Risk Analysis, 1989
AIChe-CCPS, Guidelines on Process Equipment Reliability Data with Data Tables, 1989

Industrial Risk Insurers, Plant Layout and Spacing for Oil and Chemical Plants, IM.2.5.2. June 1993


Appendix 7A. Graphical Presentation of CPQRA Results

7A.1. Overview

A number of ways exist to present the results of a CPQRA in graphical form. These are briefly described here to illustrate that portion of the CPQRA documentation task.

7A.2. Iso-Risk Contours

One method of displaying individual risk is to plot on a map of the site and surrounding areas, contours that demarcate areas exposed to equal levels of risk. CPQRA computer programs will normally calculate the individual risk level for each point in a map grid. Grid points exposed to approximately equal levels of risk can then be linked graphically by drawing contours on the grid. These are known as Individual Risk Contours or Iso-Risk Contours. A more detailed discussion of Iso-Risk contours can be found in the CCPS book, Guidelines for Chemical Process Quantitative Risk Analysis. An example of an Iso-Risk Contour plot is given in Figure 7-1.

![Figure 7-1. Example of an Individual Risk Contour Plot](image-url)
7A.3. F–N Curves

Society has generally taken a view that multiple deaths in a single incident are far worse (i.e., less tolerable) than an equivalent number of accidents involving single deaths. In other words, the frequency level at which such multiple fatalities would be tolerated is lower than for the same number of single fatalities. In order to address this perspective on tolerable risk to large groups of people, societal risk is often presented graphically, on logarithmic scales, by plotting the number of fatalities (N) in an incident; versus the frequency of occurrence (F) causing N or more fatalities. This type of risk plot is called an F–N curve. Figure 7-2 illustrates F–N curves for a number of hazardous activities. The CCPS book Guidelines for Chemical Process Quantitative Risk Analysis provides more guidance on societal risk and the preparation of F–N curves.

7A.4. References


![Figure 7-2. Example of a Societal Risk F–N Curve](image-url)
Appendix 7B. Documentation of Supporting Data

7B.1. Overview

CPQRAs are often based upon a considerable amount of data. This data should be appended to, or its origin should be identified or referenced in the summary report to enhance the creditability of the study and to facilitate auditing. This section suggests some types of supporting data that might be addressed when documenting CPQRA.

7B.2. Basic Process Data

Basic process descriptive data may be found in the following:

- material safety data sheets (MSDSs);
- process flow diagrams (PFDs);
- piping and instrumentation diagrams (P&IDs), engineering flow diagrams, utility flow diagrams;
- operating procedures;
- maintenance procedures;
- instrument test schedules;
- layout and site drawings; and
- results of any Process Hazard Analysis (PHA).

7B.3. Specialized Data

In addition, some specialized data may be required. These could include:

- meteorological (weather) data;
- demographic (population) data;
- equipment failure rate data;
- human error rates; and
- historical accident data.

Each of the above will be described in more detail, below.

Meteorological Data. These data are prepared from routine observations taken at meteorological stations, typically airports. The raw data, or processed data, can be provided from national meteorological sources. When preparing for a consequence analysis, it is not uncommon to use a 10-year collection of data to assess mean probabilities for the different combinations of wind speed, direction, and stability class. Ten years of hourly readings produce nearly 88,000 sets of observations. For each set of observations, at least four pieces of data (time, wind speed, wind direction, and cloud cover) are required to calculate a joint frequency distribution of wind speed and stability class. The method used to reduce this mass of data to the required frequency distribution should be documented together.
with the source of the raw data, and a summary of the reduced data. Justification for the choice of the method of reduction should also be documented.

**Demographic Data.** The principal sources of demographic data are census statistics produced for local areas, together with detailed local maps. An analysis will be required to relate population to defined areas, for example to a grid of appropriate dimensions, typically, 200 m, 500 m, or even 1000 m. The source of raw data, the derived demographic data and the method used to prepare them should be documented.

**Equipment Failure Data.** For an incident to occur, there must be an initiating event. While a natural disaster (e.g., tornado or earthquake) might cause a process incident, the overwhelming majority of initiating events are either equipment failures (discussed in this section) or human errors (discussed in the next section).

Historically, equipment failures result from some identifiable cause or causes. For instance, overpressure can cause a pipe or vessel to burst and the cause of the overpressure can be identified through the application of PHA (e.g., HAZOP or FTA). Alternatively, equipment can fail due to some inherent defect or due to deterioration during service caused by stress, corrosion, or wear. Over a large number of installations and a large number of years, a history of such failures can be developed, and average failure rates can be determined. Also, if the data are extensive enough, their confidence limits can be calculated.

When documenting a CPQRA it is often important to document, for each set of data used:

- their origin (in the raw form) by quoting the reference;
- what adjustments have been made to them, for instance, removal of inappropriate failures; and
- confidence limits, where available, or comments on uncertainty where appropriate.

For additional guidance on the treatment of failure rate data, see the CCPS book *Guidelines on Process Equipment Reliability Data, with Data Tables*, and the references contained in that book.

**Human Error Rate.** This is a part of many CPQRAs because human beings may be less consistent and less reliable than the equipment they operate or maintain. The human being is subject to complex emotional issues, unrelated to the job, like domestic or financial problems, as well as job-related emotional issues such as those caused by stress or emergencies. Emotional issues and ergonomic issues constitute performance shaping factors (PSF) that should be addressed in the CPQRA; consequently, the reason for selection of each human error rate used should be documented in the CPQRA. The assessment is more credible if the logic underlying human error rate estimates is properly documented.

**Historical Accident Data.** There are several objectives in documenting the accident history of the plant being considered and, where possible, of similar plants in the industry.

As discussed previously, CPQRA involves estimating the likelihood and potential consequences of serious incidents. Historical data can serve to help calibrate these estimates. Additionally, analysis of actual incidents may suggest event scenarios not otherwise identified in the CPQRA.

Pertinent accident data should be considered for inclusion, or reference, in the CPQRA documentation.

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### Appendix 7C. Other Aspects of CPQRA Documentation

#### 7C.1. Selection of Cases to Consider

One of the continuing challenges in CPQRA is selection of the basic scenarios to model. In the real world there is usually an endless spectrum of scenarios to consider and such an infinite number of combinations and permutations of events cannot be modeled. Instead, a finite set of representative cases is considered, the integration of which is intended to represent the extent of the actual situation. Describing and justifying the selection is not difficult, but requires some experience in recognizing realistic parameters. Guidance is given in Chapter 1 of the CCPS book, *Guidelines on Chemical Process Quantitative Risk Analysis*.

Documentation should indicate which scenarios have been selected and the rationale for selection. The documentation might include:

- a brief description of the selected scenarios;
  - identity of material released;
  - size of hole or other source of loss of containment;
  - mass release rate, of each phase;
  - fallout/rainout/stayout;
  - nature of dust, aerosol or vapor cloud, and its dispersion; and
  - ignition scenarios.
- the assumptions that have been made;
- the possible uncertainty in these assumptions; and
- reference to the data bases used, and any adjustments made to raw data.
7C.2. Methodologies for Consequence Assessment

The calculation of risk for an installation typically addresses a wide variety of potential events and requires the estimation of the consequences to people or equipment that can result. For example, accidental releases can lead to fires, explosions, or toxic impact. The consequence assessment methodology used for each type of event differs, and there is a need for a reader of a CPQRA to know which methodology was used, why it was selected (if there are alternatives), how it was used, and what confidence levels were assigned to the results. The following discusses some of the more important aspects of consequence modeling and suggests documentation requirements for each.

7C.2.1. Dispersion Modeling

In assessing the consequences of the release of hazardous (e.g., flammable or toxic) materials, it is necessary to model the travel and dilution (i.e., the dispersion) of the cloud. Reference should be made to the CCPS book *Guidelines for Use of Vapor Cloud Dispersion Models* and to the CCPS *Workbook of Test Cases for Vapor Cloud Source Dispersion Models* which give extensive details on the methodologies and computer programs available.

Extensive documentation is often required for dispersion modeling and might include the following:

- description of scenarios being modeled;
- reasons for selection of model used;
- validation tests of model where required (references may be adequate);
- assembly of basic input data (e.g., release rates, material physical properties);
- assembly of support data (e.g., meteorology, terrain, atmospheric data);
- assumptions made;
- selected output data (e.g., examples of printouts, tables, and graphics);
- summary output tables;
- description of results;
- sensitivity of results;
- conclusions; and
- references.

7C.2.2. Ignition, Fire, and Deflagration

Releases of flammable materials can result in a variety of undesired events ranging from pool fires to devastating vapor cloud explosions. Reference should be made to the CCPS books *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs* and *Guidelines for Chemical Process Quantitative Risk Analysis*.

In evaluating the potential consequences of an airborne release of flammable materials, it is often necessary to estimate the size of the resultant flammable cloud; dispersion calculations have been discussed in the previous section.
The variety of potential events make it impractical to specifically address the documentation requirements for each type of consequence modeling. In general, however, the documentation requirements parallel the categories of information presented in the previous section on dispersion modeling.

7C.2.3. Modeling the Consequences of Exposure to Toxic Cases

The physiological response to a toxic gas is often a complex function of both the concentration and the duration of the exposure. Modeling of the consequences of toxic gas exposure, therefore, requires estimation of both concentration and duration, calculation of an appropriate “dose” and relating this “dose” to the estimated physiological response (e.g., death or illness).

One common modeling approach is based upon the concept of the probit function. The probit function relates the exposure concentration and duration to the probability that a stated level of health effect will be experienced. Probit relationships are typically derived from animal exposure test results, that have been extrapolated to equivalent human health effects. An example is the following probit equation for fatalities due to exposure to chlorine:

\[
Pr = -8.29 + 0.92 \log_e (C^2 t)
\]

where \( C \) is the concentration in parts per million and \( t \) the duration of exposure in minutes. The \( Pr \) value is 5.0 for a 50% probability of fatality. For full details of this type of calculation see the CCPS book on Guidelines for Chemical Process Quantitative Risk Analysis.

Other approaches exist for modeling the consequences of exposure to toxics. Whatever the methodology chosen, its basis for selection should be described in the documentation of the CPQRA. It is also important to note that there is a very large number of assumptions inherent in the modeling of toxic dose consequences, that can have a profound influence on the results. These include the protocol used for the original tests to produce the animal toxicity data, the translation of results to human beings, the absence of concentration fluctuation, and the variation in human susceptibility. Where pertinent, discussions of key assumptions, and their significance, should be included in the CPQRA documentation.

7C.3. References

AIChE–CCPS, Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs, 1994
AIChE–CCPS, Guidelines for Use of Vapor Cloud Dispersion Models, 1987
AIChE–CCPS, Workbook of Test Cases for Vapor Cloud Source Dispersion, 1989