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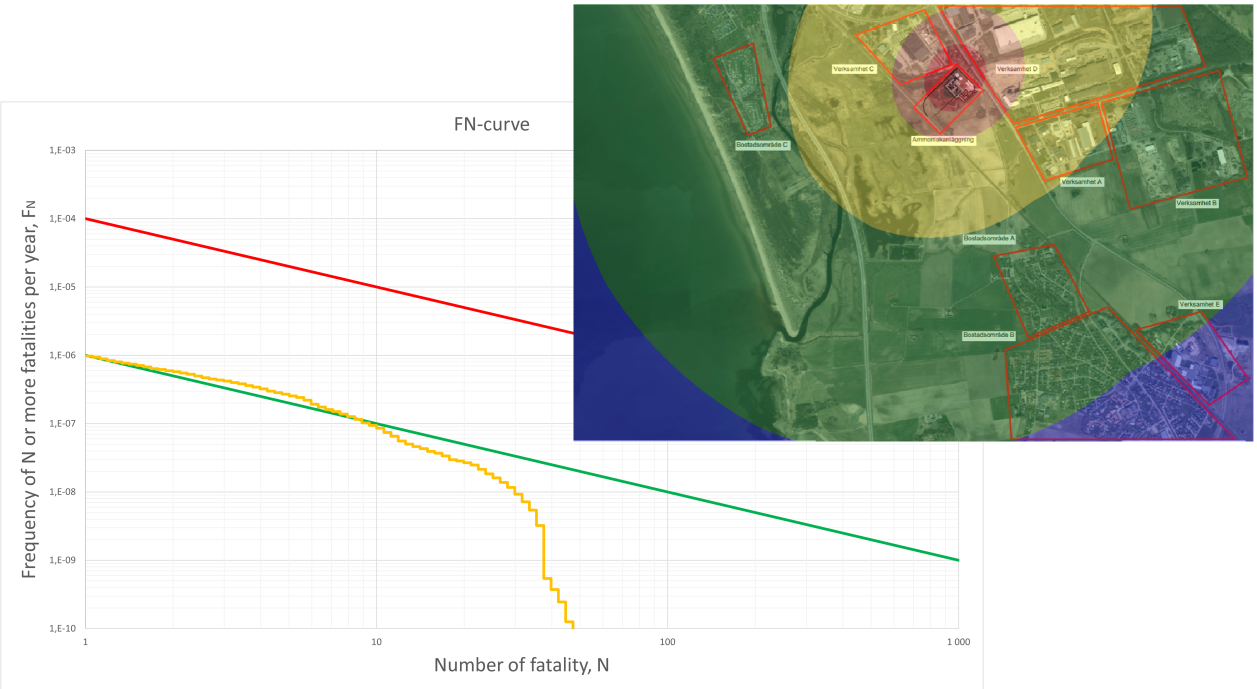

Evaluation of IPS guidelines regarding Quantitative Risk Analysis

Evaluation of the guidelines from IPS regarding when and how to perform a QRA through applying it on a fictitious site and reflecting on its merits

Master's thesis in Innovative and Sustainable Chemical Engineering

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Master's thesis 2024

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Master's Thesis 2024
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Cover: Resulting individual and societal risk illustrations.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

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Abstract

Quantitative Risk assessment can be challenging in both the amount of work that needs to be performed as well as in the amount of knowledge the risk analyst has to call back to correctly perform the assessment. To handle the amount of steps that each assessment is likely to include, the natural way to ensure that the work is consistent and reproducible between different sites is to create guidelines from which the analyst can work from.

This thesis evaluates the IPS guidelines for Quantitative Risk Assessment (QRA) to determine their practicality and utility in standardizing QRA practices in Sweden. IPS has divided the guidelines into two distinct parts: Part 1, aimed at readers without prior knowledge of QRA, provides a general overview and context, while Part 2 is intended for practitioners, offering detailed methodological guidance for performing and documenting QRA.

Key findings indicate that the guidelines are robust, incorporating established methodologies like those from the Purple Book [1] and Center for Chemical Process Safety (CCPS) [2], with some updates and adaptations to reflect current practices among practitioners in Sweden and internationally. Emphasis on transparency and the use of site-specific data enhances the reliability of QRA results. However, there is a need for more detailed guidance on interpreting results and discussing risk reduction measures.

Despite some limitations, the IPS guidelines represent a significant advancement in standardizing QRA procedures in Sweden. Future revisions should focus on clarifying completion criteria, and providing detailed interpretation guidance, thereby further enhancing the quality and consistency of QRA reports.

Keywords: IPS, QRA, quantitative risk assessment, risk criteria, individual risk, societal risk, evaluation.

Acknowledgements

I would like to begin by expressing my gratitude to my two supervisors, Sohrab Nassiri and Mats Lindgren, for their guidance, support, and encouragement. Their expertise and patience were instrumental in keeping me on the right track, answering all my questions, and helping my professional growth.

A big thanks to Jonny Danielsson from Gexcon for providing me with a license for RISK-CURVE and EFFECT, which were essential tools for the calculations in this QRA.

I would like to acknowledge the Safety team at AFRY Gothenburg for their support throughout the of this work. Their assistance and encouragement were greatly valued.

A special thanks to Gunnar Eriksson, my examiner, for giving me the opportunity to write this thesis and for being the first to introduce me to the world of process safety.

Lastly, I want to express my deepest gratitude to my friends, family, and partner. Their love and support have been my foundation helping me persevere even when it was challenging. Thank you for always being there for me.

Maria Weber, Gothenburg, June, 2024

List of Acronyms and Definitions

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

1st person	A working person at the site
2nd person	A working person at a neighboring/adjacent site
3rd person	The general public outside the site subjected to the analysis
ALARP	As Low As Reasonably Practicable. The area between the negligible and maximum tolerable risk where the risk level has to be "as low as reasonably possible/practicable" to be tolerable
Ignition, immediate	Ignition of leak immediately, at the leak point/hole
Ignition, delayed	Ignition of leak after some time. The gas cloud can spread and then ignite
API	American Petroleum Institute
BLEVE	Boiling Liquid Expanding Vapor Explosion
CCPS	Center for chemical process safety
Domino-effect	When a initial causes consequences leads to other consequences
DSB	Direktoraret for samfunnssikkerhet og beredskap
Explosion	A fast process that releases energy and produces a pressure wave
FAR	Fatal Accident Rate, the number of fatalities per 100 million working hours
Frequency	The amount a cause is estimated to occur under a given time period, usually per year
f/N-curve	A curve diagram that shows the accumulated frequency (f) against the number of fatalities (N), used to describe the societal risk

Flash fire	A fire caused by a delayed ignitions of a leak of either a vaporized liquid or a gas leak that occurs in a non-confined space without a buildup of pressure.
Vapor cloud explosion	Happens after a delayed ignition of a either a vaporized liquid or a gas leak that occurs in a confined space followed by a buildup of pressure.
Group risk	A weighted risk for a group of individuals that are exposed to the risk source that is analyzed.
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HSE	Health and Safety Executive
Individual risk	The accumulated frequency of fatality an individual at a specific location, due to any of the identified potential accidents.
ISO	International Organisation for Standardization
Jet fire	Fire that occurs following a immediate ignition of a leak of gas or liquid under pressure. The fire occurs immediately from gas or two phase.
Quantitative risk analysis	A risk analysis is where estimating the probability and consequences of identified scenarios are done in general terms, commonly with the help of a risk matrix. The probability assessment can be between different intervals (e.g. once every 10 - 100 years) or in relative terms (e.g. often, seldom, never). The impact assessment is done by a descriptive text, e.g. temporary minor discomfort, need of medical assistants or fatality.
LBE	Law regarding flammable and explosive goods.
LOC	Loss of Containment
LPG	Liquefied Petroleum Gas.
QRA	Quantitative Risk Analysis/Assessment.
Risk	A function of probability and consequence.
Risk contour	Illustrates the individual risk and shows the affected region for specific risk level surrounding the risk source.
Risk object	The operation that causes the accidents and it can contain many risk sources.
Societal risk	The accumulated frequency of potential number of fatalities.

Nomenclature

Below is the nomenclature of indices, parameters, and variables that have been used throughout this thesis.

Indices

i	Indices for a singular scenario
x, y	Indices for the coordinates

Parameters

M_{mat}	Ignition energy
MIE	Minimum ignition energy, [mJ]
M_{mag}	Source strength
FR	Source strength, [kg/s]
M_{dur}	Duration of leak
t	Time, [s]
S	Probability of ignition within 1 min from numerous ignition sources
$P_{del,ign}$	Total probability of delayed ignition
$IR_{x,y,i}$	Individual risk for coordinate x, y for the singular scenario i per year
$IR_{x,y}$	Individual risk for all scenarios at coordinate x, y per year
f_i, F_i	Frequency for scenario i per year
$p_{f,i}$	Probability that scenario i will lead to a fatality at coordinate x, y
N_i	Amount of fatality for scenario i
$P_{x,y}$	Number of people present at the coordinate x, y
F_N	Frequency for all scenarios that affect N or more prople

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1

Introduction

As the world of industry continue to expand, diverse and increase it follows that the need for sharper regulations grows. In Sweden today there are some requirements regarding the industrial activities, such as the Seveso legislation, LBE, Miljöbalken and so on. These requirements come in the form of risk analysis of varying methods. Today there are also some authorities that want to have a QRA or some companies due to their internal requirements chooses to perform a QRA. Both of these cases lack a standardized methodology of how the QRA should be formulated. In Sweden today there is no law requirement or any national guidelines for how a QRA (quantitative risk assessment) should be conducted or when it is needed [3]. This means that the practitioner themselves will decide which input data, model and forms of presentation data to use for the QRA, leading to a large variability between different QRA reports. A QRA can be used for a number of different reasons, for example basis in decision making both during the planning stages of a new plant, but also for existing plant to evaluate the current risk level and for assistance in finding solutions for further accident prevention measures.

For the last years The Swedish Process Safety Association (Intressentföreningen för processäkerhet, IPS, in Swedish), a non-profit association, together with some member companies have compiled a guidance for QRA in two parts. This is to serve as a common guideline for both when to utilize a QRA and for how to undertake a QRA with the potential of standardizing the practice of QRA:s.

1.1 History of QRA

The beginning of QRA originates from the Netherlands, specifically to be used for Land-Use Planning (LUP). Since then it has been evolved and is now used in many different areas such as the chemical industries that this paper is focused on [4].

In the 1960s the population expressed the need for greater safety regulations as the industry was expanding in a rapid pace. This need was created from frequent accidents, such as fires, explosions and leaks, that took place in the industry. It was not until some major accidents occurred that the Netherlands started to develop the needed tools to analyze safety and risk.

1.2 Aim of the project

The aim of the thesis is to evaluate the methodology, data sources and assumptions recommended by IPS through practical application to a fictitious chemical plant.

To achieve the aim the following steps will be taken:

1. Perform a QRA, based on the fictitious site, that follows the "best practice" model described in the guidelines, and also in the chapter called "Theory & Methodology" in

this thesis.

2. After completing the QRA an evaluation of the IPS guidelines will be done. The evaluation will focus on whether the guideline provide sufficient guidance to perform a QRA, and if not, what additional data is required.

1.3 Method of QRA

The method used in this paper is to first perform a QRA using the guidelines from IPS and the reflect on the ability of producing a quality QRA report.

In figure 1.1 a simple overview of the steps in a QRA is shown. A Hazard Identification is used to determine which scenarios are going to be included, IPS recommends using both generic ones from BEVI risk manual (BEVI) and specific ones that are found through a HAZID. Then the frequency analysis is done closely followed by the consequence analysis. When both of those steps are completed now it is possible to calculate and assess the risk. Once these steps are completed next is to manage the uncertainties for the data sources and models used for the risk assessment. The final stage is to ensure the quality of the report by having a transparent approach in every step and stage, and also to document the background of both the one doing the report but also the ones participating and are used as experts.

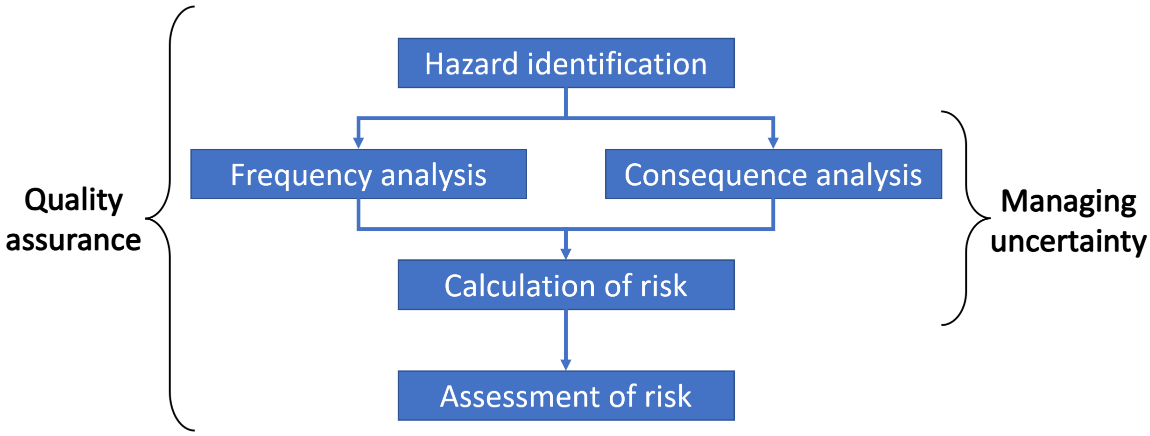


Figure 1.1: An overview of the methodology for a QRA [5]

1.4 Limitations

The scope of a QRA is normally to only include accidental releases of hazardous materials. In other words, scenarios that potentially may occur because of an intentional circumstance (e.g. sabotage or terrorism) are not included. In addition, the objective of a QRA is to quantify the risk in terms of the risk for individuals outside of a site to perish as a result of accidental releases from the site.

There will be a limit placed on the amount of scenarios that will be analyzed, between 10 and 30. This is due to time constraints. When identifying scenarios at most 50 will be considered. From these 50 a process is used to limit the number of scenarios based on the relevance to the process site and surrounding areas, the available data for calculations and competence of the student.

1.5 Outline of the thesis

Chapter 1 of the thesis is the introduction, giving a brief description of the purpose for the thesis and the underlying need for it. It also shows the limitations and a brief description of the method used in the QRA. Chapter 2 gives the reader the necessary background and knowledge to understand and follow along with the reasoning used and the method used in the thesis both for the QRA and for the evaluation of the IPS guidelines. Chapter 3 presents the results and discussions around the results, and is divided in two parts. First part is the QRA report written as recommended by the IPS guidelines and the second part is the evaluation of said guidelines. Chapter 4 contains the conclusions of the thesis.

1.6 Stakeholders

The primary stakeholders in the project are the student, Chalmers and IPS. These are the entities with the most to gain or lose from the project. The student's aim is to pass the examination, Chalmers aims to uphold certain standards for thesis, and IPS seeks to produce a valuable and valid guidance document for QRA. Additional stakeholders are AFRY and Gexcon. AFRY played a significant role in developing the guidance and providing practical insight into QRA practices in Sweden's industry today. Therefore they are likely interested in ensuring the quality of the document promote themselves as QRA experts in Sweden. Gexcon provided the student with the software tool used throughout the project and would ensure a positive perception of their software to encourage its further usage.

1.7 Bias and subjectivity

The student writing this thesis is employed by AFRY and attends Chalmers University of Technology. Though the thesis comes from IPS, AFRY has been a major part in its development. In addition, experts that have assisted the student are associated with the aforementioned stakeholders.

When conducting the project the student will be vigilant in not forming biased opinions to ensure the objectivity of the results and conclusion. As this study is done to evaluate the guidance and if the results are biased this will negatively impact the guidance future usage.

2

Theory & Method

The following chapter is divided into two sections. The first focuses on the QRA report and the relevant theory and methodology. The second section details the theory and methodology relevant for evaluation of the IPS guidelines with regards to the practical implementations.

2.1 QRA theory and method

As there is no established procedure for conducting a QRA in Sweden, this method is what IPS is proposing to be made into the standard procedure and the method this thesis has followed. In figure 2.1 an overall flow sheet shows the seven core parts of the methodology proposed by IPS. This chapter describes the methodology used in the thesis and the underlying theory. For a more comprehensive methodology it it recommended to read the IPS guidelines.

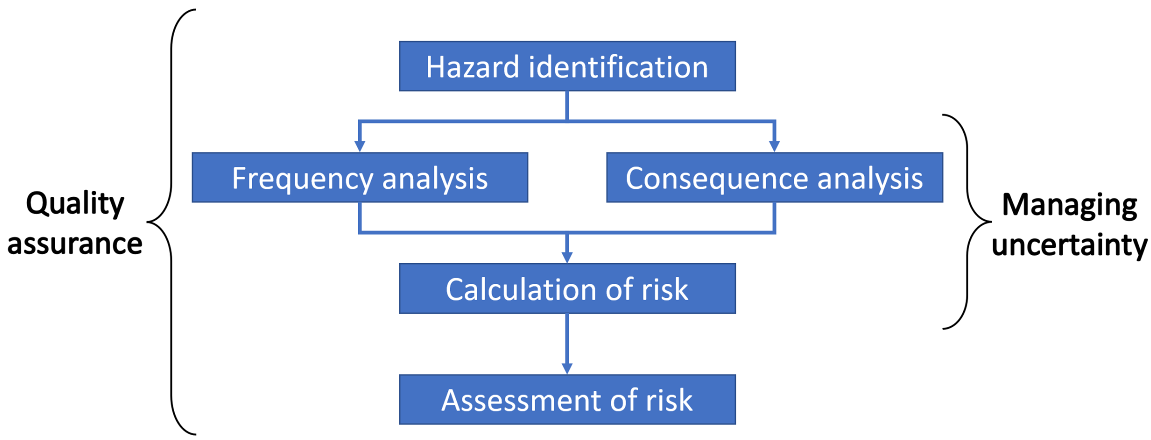


Figure 2.1: An overview of the methodology for a QRA [5]

2.1.1 Hazard Identification

What is meant by a scenario is the unintentional release of a hazardous substance, also called loss of contaminate (LOC), and the sequence of events following that has the potential to lead to a fatality outside of the process site. A scenario is composed of a "cause", "partial events" and then the "final outcome". The outcome is the event from where the consequences will be calculated, while the cause event determines the frequency used. Selecting the scenarios is the backbone for the rest of the QRA, meaning that they have to represent an accurate portrayal of reality of the risks and their implications.

2.1.1.1 System definitions

The method used to decide the scenarios can greatly impact the results and quality of the QRA. It is also very important to present the progress from the leak to the final event. But before this is undertaken it is necessary to define the system. This entails to decide what is a risk object, an installation that can cause a severe chemical accident and that contains more than one risk source, object of protection (is an object that needs to be protected from the risk object and risk sources), who are the people that the consequences will be calculated for, which type of risk will be calculated (individual and/or societal risk), what are the criteria on the risk levels for the risk to be tolerable. It is also important to, on a coarse level, describe the chemical processes of the site, the different components and list the chemicals handled.

Many of the things needed for the system definitions were predefined and given as input data for the fictitious plant. The design of the plant was on a coarse level. This simplified the system defining steps. Regarding the surrounding area outside of the site this was also predefined and given at the start of the project. The plant design and population data, are available in appendix A.5 and A.1 respectively, in chapter 3 section 3.1.1 a brief description of the process is written. For certain parts of the process a few dimensions were missing, engineering judgment was used to estimate the dimension form other parts of the plant.

2.1.1.2 Hazard identification

The next step of the QRA is to undertake a hazard identification. A normal limitation for QRA is that the accident/incident must have the potential of resulting in a fatalities that occur outside of the sites area.

As mentioned above a scenario is initially segmented into a "cause" and a "final outcome". The cause entails the occurrence of the loss of containment, LOC, wherefrom the frequency is calculated, whereas the final outcome represents the consequence that the risk is calculated for. There are two types of causes that the guidance uses, the generic cause and the specific cause. For the generic causes the underlying reason for its occurrence is not of interest as it can be considered common or the availability of ample reliable data. But for the specific cause the underlying reason is of importance for estimating the frequency of the event [5].

The generic causes are identified by following the structure of the Bevi Risk Manual (BEVI), [6]. The method outlined here follows a structure where the type of equipment is first identified and then BEVI gives the relevant scenarios and their respective frequencies. Examples of equipment types mentioned in the BEVI are pressure storage tanks both above and below ground, pipelines, reactor vessels, transport units, and others, totaling 12 different categories.

To identify the specific causes a preliminary risk analysis is typically conducted prior to the QRA. In the case of this thesis, a HAZID was performed by the student. This method aims to find any unique potentially hazardous scenarios for equipment and/or chemicals specific to the relevant process. Example of potential specific causes include runaway reactions and BLEVE.

2.1.2 Frequency analysis

The frequency of a scenario is the estimated amount of times the scenario might occur per year. All of the generic scenarios have predetermined frequencies, based on the sources used. The specific scenarios require the QRA professional to estimate a frequency for these.

2.1.2.1 Frequency of cause

Once cause is established next step is to determine the frequency of it, which involves assessing how often a specific event, such as the failure of a pipe, is likely to occur within a given timeframe, generally per year. This can either be achieved by finding generic data sources or by relying on a experts judgment, alternatively through calculations.

2.1.2.1.1 Generic scenarios

IPS recommend that generic data sources are used for generic scenarios. However if the site have internal frequencies for the cause, then this is preferred as it likely improves the results relevance for that specific site. If such internal sources is not available then IPS recommends Bevi Risk Manual [6] for most of the components. Though the use of generic data has a negative impact on the relevance of the results for a specific site, it allows for greater comparability of the results with other QRA:s using the same data source. However, the source has to be reliable an the calculations done with a sufficiently large dataset to be able to form realistic conclusions.

2.1.2.1.2 Specific scenarios

For the specific scenarios it might be necessary to perform a fault tree analysis. This type of analysis looks at what different underlying causes could lead to the scenario. In figure 2.2 a full fault and outcome analysis can be seen for a singular scenario.

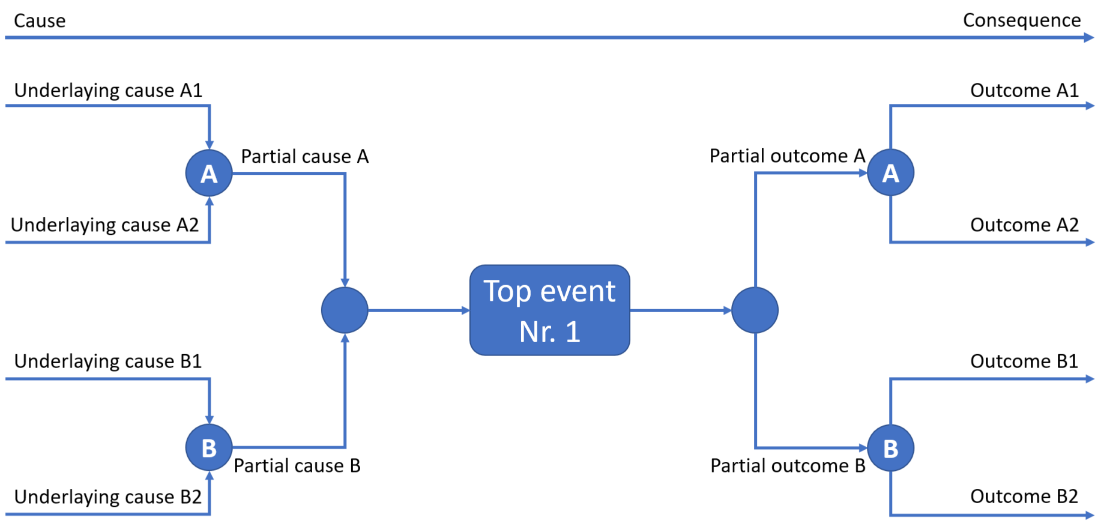


Figure 2.2: Illustrating a scenario from different underlying causes to different final outcomes also called bow tie, [5]

In cases where a cause lacks a frequency, it may be possible to derive frequency from underlying causes associated with it, allowing calculation of the frequency for the cause to the scenario. Other times the cause can have a frequency from a different source. If it proves to be too complicated, complex or the underlying causes do not have frequencies it could be appropriate to have an expert make a judgment call. This judgment call should be done by an individual with an extensive background in the subject and with a conservative estimation. In QRA to be conservative entails overestimation of the risk or value are preferred to ensure that the results do not underestimate the risk assessment.

2.1.2.2 Weather conditions

An important factor for the risk is the weather conditions particularly regarding the dispersion of gas in air. Three distinct categories, wind directions, wind speeds and the stability classes, collectively make up the weather conditions used in QRA calculations [5]. IPS recommended utilizing SMHI if any of the information is unavailable.

Some of the types of scenarios are less dependent on the weather conditions, while others are heavily dependent on them. For instance, BLEVE and pool fires are examples of scenarios that are less dependent. Instead scenarios resulting in toxic cloud formation are highly dependent on both the type of wind speed and stability class.

To properly show the weather conditions used in the analysis a matrix that integrated all three categories is recommended by IPS. This matrix is used as input for software to describe the weather conditions. IPS gives three recommendations for both the wind speed and then the stability class depending on the time of day, either day or night [5].

- Low wind speed - 2 m/s with stability class B (day) and F (night)
- Medium wind speed - 5 m/s with stability class C (day) and D (night)
- High wind speed - 8 m/s with stability class D (day and night)

Table 2.1 shows how the different wind speed and stability result in a large variety of weather conditions and how they translate to reality. To put the different types of combinations into a more contextualized perspective, a 8D day is a warm and windy summer day, whereas a 2F could be a cold, cloudless winter night.

Wind speed	Day:Solar radiation			Night:Cloud cover	
(m/s)	*Strong*	*Medium*	*Low*	*> 50 %*	*< 50 %*
<2	A	A-B	B	F	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	F
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

Table 2.1: Variation of stability classes with wind speed, time of day, cloud cover and sun radiation, [7]

Once the wind speed and stability classes have been determined the final necessary data is the distribution of the wind direction. This is not something that can be set to a standard in the same way as for the speed and stability. This is dependent on the geographical position of the site that is being analyzed. IPS recommends to use the SMHI database for the specific location of the plant being analyzed. This data is based on historical measurements and already divided into the different wind sectors. There are a total of 12 different wind sectors, this is done by dividing the 360 degrees into 12 different segments.

2.1.2.3 Immediate and delayed ignition leading to fire/explosions

A leak of a flammable material can be ignited, leading to a fire/explosion event. The ignition can take place either immediately, later (delayed) or not at all. In order to quantify these steps the probability of immediate and delayed ignition needs to be determined.

2.1.2.3.1 Immediate ignition

For determination of the probability of immediate ignition the IPS guidance recommends to follow one of the methods described in BEVI [6]. This is done by first categorizing the substance based on its flashpoint or boiling point depending on the relevant physical phases, see table 2.2 for the specifics regarding the different categories. The different substances SDS (Safety Data Sheet) are used to find this information.

Substance category	Definition
Category 0, high reactivity	Liquid with flashpoint < 0 °C and boiling point ≤ 35 °C, gaseous substances that can ignite at normal temperature and pressure
Category 0, low reactivity	Liquid with flashpoint < 21 °C, however not extremely flammable
Category 1	Liquid with 21 °C ≤ flashpoint ≤ 55 °C
Category 2	Liquid with 55 °C ≤ flashpoint < 100 °C
Category 3 & 4	Liquid with flashpoint > 100 °C

Table 2.2: Categorization of substances based on flashpoint and boiling point, [6]

After this is done then the probability can be discerned by type of release, e.g. continuous or momentary, and the source strength by following table 2.3.

Substance category	**Source strength** (continuous release)	**Source strength** (momentary release)	**Probability of immediate ignition**
Category 0, high reactivity	< 10 kg/s	< 1000 kg/s	0.2
	10-100 kg/s	1000-10000 kg/s	0.5
	> 100 kg/s	> 10000 kg/s	0.7
Category 0, low reactivity	< 10 kg/s	< 1000 kg/s	0.02
	10-100 kg/s	1000-10000 kg/s	0.04
	> 100 kg/s	> 10000 kg/s	0.09
Category 1	All	All	0.065
Category 2	All	All	0.01
Category 3 & 4	All	All	0

Table 2.3: Probability of immediate ignition on stationary installations based on substances categorization and source strength [6]

2.1.2.3.2 Delayed ignition

For the probability for delayed ignition, there are three distinct methods recommended. The first method, as outlined in BEVI, is specifically made for the software SAFETI and is recommended only to be used in combination with that program. The second recommended method is called Ignition Probabilities from IOGP, [8], and is used for petroleum based products. For substances not falling within that category then the Moosemiller method should be used [9].

The base assumption in the Moosemiller model is that the probability of a delayed ignition is equal to 0.3 but then modified based on three new dimensionless numbers. These numbers take into account the ignition energy (M_{mat}), source strength (M_{mag}) and lastly the duration (M_{dur}) of the leak. M_{mat} is calculated as shown below:

$$M_{mat} = 0.6 - 0.85 \cdot (\log(MIE), \quad 0.1 \leq M_{mat} \leq 3 \tag{2.1}$$

MIE is the minimum ignition energy in the unit mJ.

$$M_{mag} = 7e^{0.642 \cdot \ln\left(\frac{FR}{0.4545}\right) - 4.67}, \quad M_{mag} \leq 2 \tag{2.2}$$

FR is the source strength in kg/s.

$$M_{dur} = \frac{1 - (1 - S^2) \cdot e^{-(0.015 \cdot S) \cdot t}}{0.3} \tag{2.3}$$

t is time in seconds and is specified to be 60 seconds, and S is the probability of ignition within one minute from numerous ignition sources. IPS also recommends four different values for S dependent on the density of the equipment.

- High equipment density: 0.5
- Medium equipment density: 0.25
- Low equipment density: 0.1
- No equipment: 0.02

The way to choose the value for the equipment density is subjective and is a source of uncertainty. However, by applying the conservative approach only when it is needed as to not over estimate the risk, also leading to a unrealistic result. This is however dependent on the substance as most toxic substances pose a greater risk as a toxic cloud, as apposed to a fire. The resulting probability can then be used as input for the calculation of risk and consequence.

$P_{del,ign}$ is the total probability for a delayed ignition and is calculated according to the following three equations 2.4, 2.5 and 2.6.

$$\prod M_i = M_{mat} \cdot M_{mag} \cdot M_{dur} \tag{2.4}$$

$$P_{del,ign} = 0.3 \cdot \prod M_i, \text{ if } \prod M_i < 1 \tag{2.5}$$

$$P_{del,ign} = 1 - \frac{0.7}{\prod M_i}, \text{ if } \prod M_i > 1 \tag{2.6}$$

2.1.3 Source strength

As scenarios form the basis in a QRA, these scenarios must be elaborated on both in the way of their source strength and the airborne amount is important [5].

When determining the source strength several inputs are required, such as the type of leakage (momentarily or continuous release), the substance properties, and the operational conditions. Once the source strength is calculated the duration of the leakage is calculated based on the available amount of the source and/or how long until the leakage is stopped. If the released chemical undergoes a phase change to vapor and therefore becomes airborne this needs to be considered. The likelihood that the chemical flashed (undergone phase change from liquid to vapor) will depend on a number of parameters, for instance the properties of the chemical, handling temperature and pressure, etc.

For this thesis a software developed by Gexcon called RiskCurve version 12.0.1 was used, which is one of the programs that IPS mentions in the guideline [5]. In this program the source strength will be modeled based on a number of different models presented in the validation documentation. Validation documents are available to ensure the appropriate models are utilized for calculations. To model the source strength accurately, the program requires parameters for the relevant part of the process. These were found and specified in the data provided about the site by AFRY. Some parts of the input were needed to be estimated by comparing other parts of the process with similarities and forming a conclusion based on that.

2.1.4 Consequence analysis

The purpose of the consequence analysis is modeling the affected area for the LOC of the hazardous substance. Most of the necessary data needed for these calculations was provided by the previous sections. Figure 2.3 shows the different types of outcomes that can happen from a leak of a hazardous substance.

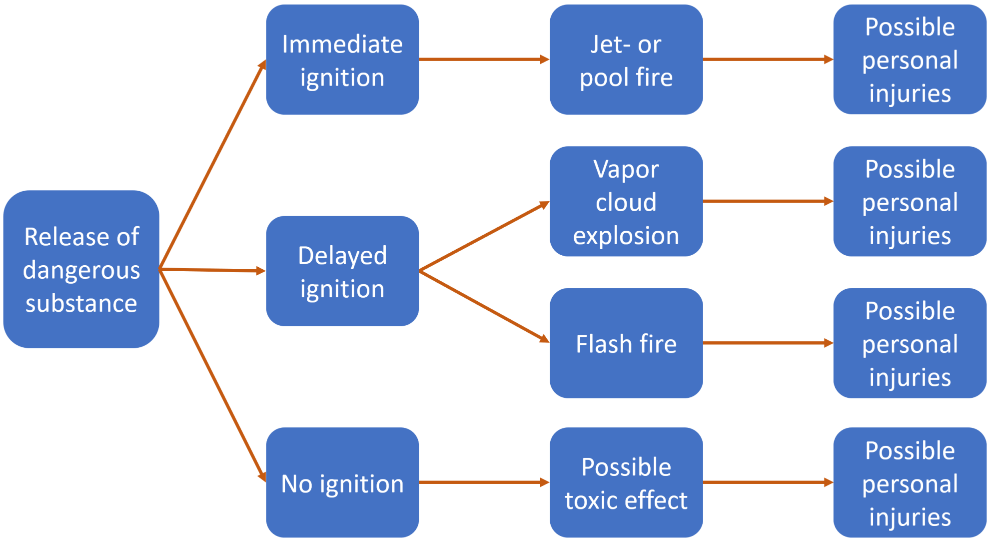


Figure 2.3: Possible sequence of event from a normal leakage of dangerous substance [3]

One of the input needed that can have a significant impact on the consequence is the topography of the environment. This is especially significant for the spread of gas cloud. A common method to evaluate the topography is using the concept of "surface roughness". Surface roughness is based on the roughness length for the terrain, this is a length-scale for the wind speed over a area and the roughness for the area. If the area is very rough then the wind will slow down as the obstacles absorb some of the winds kinetic energy. The IPS guidance recommends using 0.25 m if there is a lack of information regarding the surrounding area/environment. In table 2.4 the different types of roughness lengths available in RiskCurve is shown with the description of the ground and the respective length.

Description	**Roughness length** [m]
Open water, at least 5 km	0.0002
Mud flats, snow, no vegetation	0.005
Open flat terrain, grass, few isolated objects	0.03
Low crops, occasional large obstacles, x/h > 200	0.1
High crops, scattered large objects, 15 < x/h < 20	0.25
Parkland, bushes, numerous obstacles, x/h < 15	0.5
Regular large obstacles coverage (suburb, forest)	1.0
City center with high- and low rising buildings	3.0

Table 2.4: Showing the different types of roughness lengths used in RiskCurve, [10]

As previously mentioned all calculations from source strength to risk assessment were conducted using RiskCurve from Gexcon. However, when relying on software for these calculations the practitioner has to ensure that the recommended models and criterias are used.

2.1.5 Calculation of risk

When the consequence area has been modeled the next step is to determine the consequences to people, also referred to as the vulnerability criteria. This involves describing the level of exposure or dosage that leads to fatalities [5]. For toxic substances, the dosage is determined by multiplying the exposure time with the concentration. For fires the dosage is measured by radiation intensity. The following table, table 2.5, provides a summary of the criteria taken from the IPS guidelines is shown.

Final outcome	Criteria	Comment
Toxic gas	Probit function for poisonous gas.	For people indoors can the concentration be reduced with a factor of 0.1. Max exposure time is sett to 30 minutes.
Gas cloud fire	Within the LEL when ignition occur, the probability of death =1. Outside of LEL, probability of death =0.	Persons inside are assumed to be protected.
BLEVE	Inside the flame and radiation > 35 kW/m^2 probability for death = 1. Outside of flame and radiation < 35 kW/m^2 use Probit function.	Persons inside are assumed to be protected. Max exposure for fire is sett to 20 seconds.
All other fires	Inside the flame and radiation > 35 kW/m^2 probability for death = 1. Outside of flame and radiation < 35 kW/m^2 use Probit function. Fixed criteria in the second instance.	Persons inside are assumed to be protected. Max exposure for fire is sett to 20 seconds.
Explosion	Explosion pressure > 0.3 barg, probability for death = 1, inside and outside. Explosion pressure 0.1 - 0.3 barg, probability for death inside = 0.025, probability for death outside = 0. Explosion pressure < 0.3 barg, probability for death = 0, inside and outside.	

Table 2.5: Summary of vulnerability criteria from the IPS guideline [5]

These criteria were incorporated into the program's risk criteria to ensure that the appropriate level of risk complied with IPS:s recommendations. An additional crucial input needed is called population data, which was provided by IPS and AFRY, see appendix A.1. This data is the distribution of the population in the surrounding area of the process site. It can be defined in different ways but for this thesis it was done by segmenting the area into three residential areas and five other operation areas, see figure 2.4 for the different segments.

Figure 2.4: Overview of the surrounding area of the process site.

Then the amount of people present at each segment can either be defined strictly or for residential areas they can be defined by what type of buildings there are. In table 2.6 taken from IPS guidelines, is shown that the type of building gives the number of people.

Type of Building	People distribution
Villas	2.7 people per household
Apartments	1.9 people per household
Office	1 person per 30 m^2 BTA
Storage	1 person per 200 m^2 BTA
Hotel	1.5 person per room

Table 2.6: Data for people distributed in various types of buildings, [5]

The people present is also time dependent. This is divided by day or night time, per the recommendations the BEVI day distribution is used. The fraction for the day is 0.44 and represent the time from 08:00 to 18:30, while the night fraction is 0.56 and represent the time from 18:30 to 08:00 [6]. Lastly the distribution of the population can be considered temporary especially on the segments that are places of work. This will then be incorporated and the time spent in the segment specified, it could be 40 hours a week.

As mentioned in the introduction the standard way of displaying the risk is both by an individual risk contour and by a societal risk diagram. The methods for calculating these are described in the following sections.

2.1.5.1 Individual risk

The individual risk represents the probability of a person staying at a specific location 24 hours per day every day of the year dying [11]. This location can be a specific coordinate or a region. The placement of the risk source, wind direction, whether the person is outside and does not take any protective measures and lastly the duration of the risk are necessary information to calculate the individual risk. Equation 2.7 shows how to calculate the individual risk for the coordinate *(x,y)* for the singular scenario i per year ($\mathrm{IR}_{x,y,i}$), while equation 2.8 is the individual risk for all scenarios at the coordinate *(x,y)* per year ($\mathrm{IR}_{x,y}$).

$$IR_{x,y,i} = f_i \cdot p_{f,i} \tag{2.7}$$

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \tag{2.8}$$

f_i is the frequency for scenario i per year and $\mathrm{p}_{f,i}$ is the probability that scenario i will lead to a fatality at the coordinate *(x,y)* [5]. The probability is dependent on a number of different factors, for instance the wind distribution, e.g. wind rose.

The standard way to present the individual risk is through a contour map of the area, it uses standard values such as 10^{-5} per year, 10^{-6} per year, 10^{-7} per year and so on, centering from the release point [11]. When illustrating the total individual risk for multiple sources, then risks are added together to create a new singular contour map. These type of calculations were performed by RiskCurve when running a scenario or multiple scenarios. For this calculation IPS recommends having a grid resolution of 50x50 meter.

2.1.5.2 Societal risk

Societal risk provides an indication of the risk an affected population is exposed to [11]. This is achieved by converting the effected area, determined through the consequence analysis into the amount of potential fatalities. Essential factors in this conversion process include the spread of the affected area, population data, and the time of day when the incident occurs.

A crucial aspect of this is the population data, in Appendix A.1, the surrounding areas are described accordingly to the given data for the fictitious site, and additional information on assumptions for the distribution of people throughout the day and also for different types of regions in the relevant surrounding environment. In the following equation the method used to calculate the societal risk is presented.

$$N_i = \sum_{x,y} P_{x,y} \cdot p_{f,i} \tag{2.9}$$

$$F_N = \sum_{i} F_i, \text{ for all scenarios } i \text{ where } N_i \geq N \tag{2.10}$$

N_i is the amount of fatalities for scenario i, $P_{x,y}$ is the amount of people present at the coordinates x,y, F_N is the frequency for all scenarios that effect N or more people and F_i is the frequency for scenario i [5]. With N_i and F_N values a FN-curve can be drawn, this is the most common way to illustrate the societal risk. The FN-curve shows the correlation between the frequency of scenarios involved with N fatalities (y-axis) as a function of the accumulative number of fatalities (x-axis).

2.1.6 Assessment of risk

During the risk assessment the sites potential impacts on the surrounding areas and population are considered. Sweden does not have national criteria for defining what constitutes a tolerable risk [12].

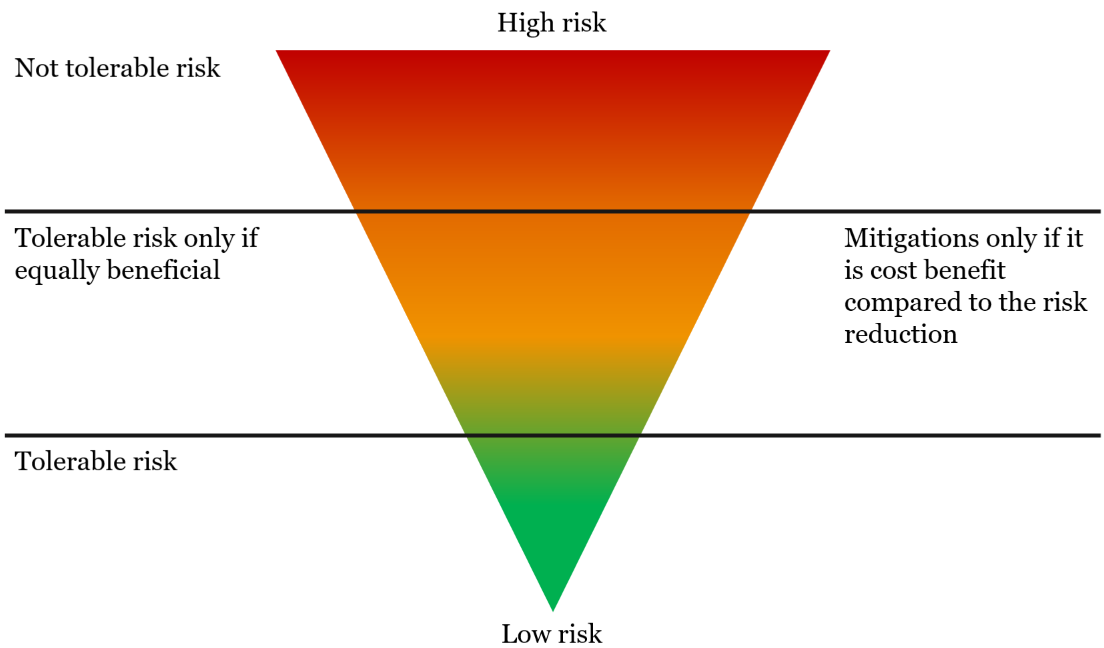


Figure 2.5: The principles for risk assessment by IPS [12]

Figure 2.5 displays that the risk assessment is divided intro three categories tolerable risk, only tolerable with mitigation, and not tolerable risk. For the intermediate risk level, also referred to As Low As Reasonably Practicable (ALARP), it implies that there the risk must be reduced through mitigation, but the extent of the risk reduction is determined by both the practical feasibility and the economical viability.

Different criteria apply depending on whether it pertains to individual risk or societal risk. In this thesis, it is assumed that the site under the designing stage and is yet to exist, therefore the criteria are different compared to those for preexisting sites. Table 2.7 shows the criteria for individual risk.

Maximum tolerable risk	1×10^{-6} per year
Negligible risk	1×10^{-8} per year

Table 2.7: The individual risk criteria for new establishments, [5]

The societal risk has a maximum tolerable risk for new establishments is represented by a line drawn between 1 fatality per 10000 years and 100 fatalities per 1000000 years. And the ALARP:s lower limit is 100 times lower than the upper limit see figure for a reference, [5].

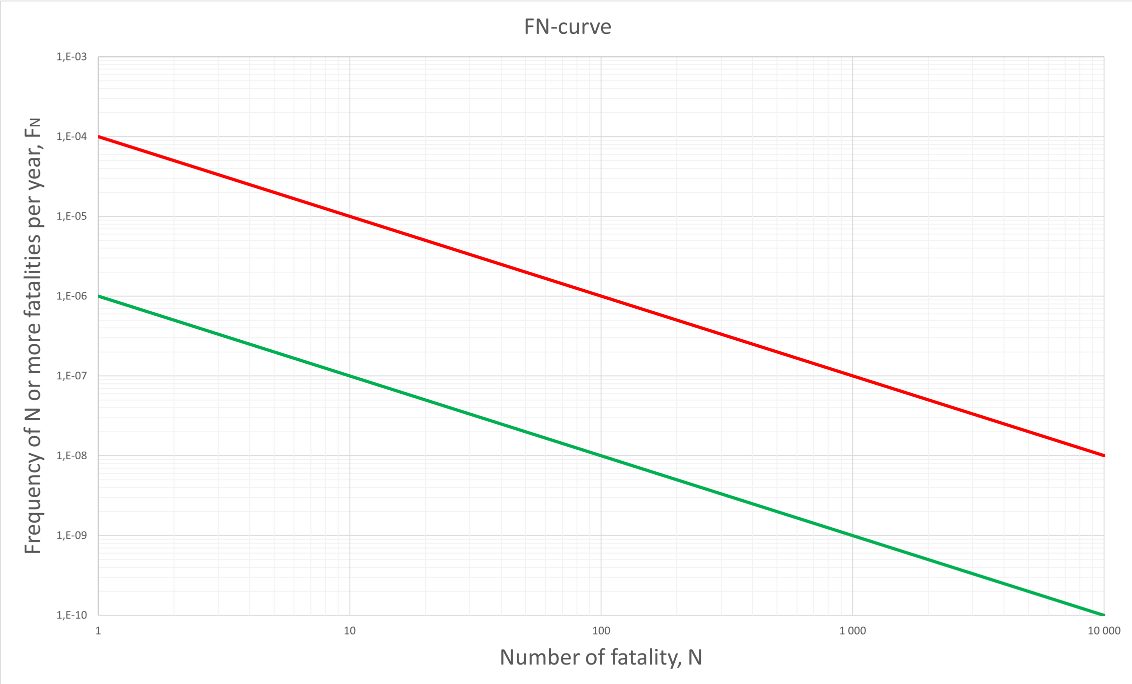


Figure 2.6: Blank societal risk curve, red represent the upper criteria limit and the green represent the lower criteria limit.

As evident, the risk criteria are typically numerical or quantitative, facilitating the comparative risk assessment across different QRA-reports. However, the interpretations regarding the stringency of the two criteria vary. While some regard them as strict thresholds that should never be exceeded, others interpret them as reference points indicating areas for improvement. One reason not to strictly adhere to these criteria is the inherent uncertainty associated with both individual and societal risk calculations. Additionally, there are some fixating on the numerical values, potentially overlooking risks that, although deemed insignificant by criteria, could still result in significant consequences. These risks are characterized by having a low frequency but a catastrophic outcome, but the low frequency makes the risk assessment to tolerable. Nonetheless it is important that the decision makers remain mindful of such risks when implementing risk reduction mitigations.

2.1.7 Managing uncertainty

For the purpose of the following segment the term "uncertainty" referrers to the considerations regarding the appropriateness of scenarios, the validity of calculation models, and the relevance and accuracy of input data. The uncertainty will be addressed in this thesis through a sensitivity analysis. This analysis will examine assumptions and parameters with the greatest significance on the results to provide insight on their effect on the resulting risks [5]. Table 2.8 provides a list of different sources of uncertainty and their respective underlying reasoning.

Sources of uncertainty	**Definition**
Scope	Are the limitations appropriate? Has any part of the process not been included?
Identifying risk	Are all of the scenarios that can affect the object of protection included? Has all of the calculated cases been chosen appropriately?
Model	When combining a number of models for calculations, they all having their own uncertainties, the combination can have a exponential larger uncertainty.
Parameter	Generic data sources will add uncertainty as it is not specifically for that component. Choosing the level of exposure causing death will be based on a generic human and some will die at lower levels (and higher levels).

Table 2.8: Sources of uncertainty [3]

2.1.7.1 Sensitivity analysis

Throughout the analysis, countless different data sources and models contributed to the final risk assessment. To ensure the robustness of the results the inputs and assumptions are tested. IPS recommend conducting a sensitivity analysis to validate this. The analysis is carried out in two stages, first stage involves identifying the most probable variables having a great effect on the resulting risks. These may include factors such as the size of the storage tank, population data, filling degree, wind direction/speed, among others.

Once the the variables are identified the second stage begins by varying the variable by a factor 2, meaning division of 2 and multiplication of 2, to assess their effect on the resulting risk. It is of great importance that only one variable is changed at a time to clearly indicate the effect of the variable. If the resulting risk exceeds the upper limits in either individual risk or societal risk then the variable is deemed sensitive, necessitating a closer inspection of its data source to ensure the resulting risk comes from the most relevant and accurate data. Conversely, if no significant change is observed the variable is considered stable and reliable.

By conducting this sensitivity analysis the uncertainty in the QRA is said to be handled. Uncertainty has the propensity to propagate due to the diverse array of sources used in assessing the risk. Everything from the assumption of the state of the process, dispersion models, ignitions models, and numerous other variables contribute to the possibilities of reaching an inaccurate risk assessments. However, by consistently documenting the sources and the reason behind their selection, as well as performing this sensitivity analysis assists to mitigate the impact of uncertainty on the overall risk assessment.

2.1.8 Quality assurance

As previously mentioned before the QRA serves as a basis for decisions, often regarding permissibility processes for an installation. Therefore, the quality of the report is of foremost importance. Central to this quality assurance is the handling of uncertainties, explained in the preceding section. But also by providing complete transparency in the assumptions made both when and why along with the reason behind using the chosen data sources. Furthermore, the competence of the participants involved the study, such as the author of this rapport, the supervisors, and other experts that assisted in the analysis.

Throughout the course of this thesis the student has consistently met with the handlers from both AFRY, Sohrab Nassiri, and IPS, Mats Lindgren, and also a representative from Gexcon, Jonny Danielsson. These meetings have served as opportunities for the student to present their progress by presenting the tasks completed, and then outline forthcoming steps, and explain the underlying rationale guiding decisions made during the research process.

Once the student had finalized all calculations in RiskCurve the results underwent a thorough examination by Sohrab Nassiri to verify the accuracy of the inputs and settings, such as the models and criterias. Furthermore, both handlers proofread the report before submission, ensuring that the interpretations and conclusions drawn were correct and credible.

2.2 Evaluation of IPS:s guidelines theory and method

The aim of this thesis is to evaluate the IPS guidelines for a QRA, this is accomplished by performing the QRA using the above mentioned methodology, while also noting any aspects that require clarification or supplementation within the methodology. Throughout the implementation of the various steps, observations were made regarding how adequate the guidelines were. After the completion of the QRA a reflective analysis of the IPS guideline was conducted by discussion on how reasonable, helpful and identifying any potential areas for improvement that was observed during the implementation if the guideline. The evaluation will finish with a statement regarding whether the IPS guidelines can be established as a standardized framework for QRA procedures.

To properly evaluate the guidelines a structured framework of how the evaluations should be conducted is needed. This framework should assist in finding significant reflections. The first and foremost criterion of any guideline is clarity in stating its purpose and scope. This clarity ensures that the reader has the necessary context to understand the information and work presented. Furthermore, it is beneficial if the guideline explains how it will ensure that the intended purpose is achieved.

Evaluation structure	**Definition**
The purpose and scope of the guidelines	When reading a guideline it is important to clearly define the purpose and how the guideline itself can ensure that the participant to reach this purpose.
Evaluation criteria	Accuracy: How accurately does the method identify and assess risks? Is the result representative of reality?
	Completeness: Are all of the risks identified and all of the outcomes calculated?
	Consistency: Does the guidance produce consistent results even when different people preform the QRA?
	Validity: Are the principles and assumption based on sound judgment?
	Transparency: What does the guidance say on how to show transparency from scenarios identification, data sources and assumptions?
	Resilience: Can the guidance be used for different types of sites/processes? Is it able to adapt to changes and different starting point?
	Practicability: Is the guidance practical in all of the expected work and assumptions?
	Robustness: Does it take into account uncertainties? And if so, how?

Table 2.9: The different categories that structure the evaluation of the IPS QRA guidelines

Following the assessment of whether the purpose and scope are clearly conveyed, the evaluation criterias are outlined, see table 2.9. These criteria encompass accuracy, completeness, consistency, validation, transparency, resilience, practicability, and robustness. The accuracy pertains to how effectively the guidance represents reality, considering the recommendation for choosing the scenarios, models, data sources and so forth. Completeness evaluate the inclusion recommended for the relevant subjects and scenarios for a complete risk assessment. Thereafter comes the consistency regarding producing quality QRA-reports, with the writer only needing a background in process technologies and process safety regardless of the writer's prior experience in writing a QRA or available resources. The validation procedure assesses the suitability and relevance of the methods, data sources, and assumptions utilized within the given context. Once the validation is examined, the guidance recommendation for transparency comes next. This involves examining how the guidance suggests ensuring that all relevant information is clearly presented in the report. The guidance should be resilient enough to enable its applicability across diverse industries and sites while consistently producing accurate and reliable results. Next comes the practicality of the guidance, this pertains to if all the expected work and assumptions needed are valid and not excessive or insufficient to form the risk assessment. It is also important to evaluate the robustness of the guidance, this refers to how well it handles uncertainty. Upon using these criteria a comprehensive evaluation of the guidance should be achievable.

3

Results & Discussion

This chapter is divided into two sections. The first section pertains to the results and discussions derived from the QRA. The second section addresses the evaluation results and discussion.

3.1 QRA Report

The following section shows a partial QRA report as some parts have already been discussed in the previous chapter.

3.1.1 Site description

The fictitious site has been designed for the specific purpose of testing the QRA guidelines. The site is an ammonia production plant. Support systems such as cooling water, steam production, process air, etc. have not been included in the schematics. In the start natural gas (methane) is mixed with steam before entering the primary reformer, converting to hydrogen gas and carbon monoxide. The cleaned air (oxygen, O_2 and nitrogen, N_2) is added to the system at the second reformer, to further convert the methane. After the secondary reformer the product is transferred to the synthesis gas reactor where the carbon monoxide is converted to carbon dioxide. The exiting gas is compressed and sent to the scrubber to remove the carbon dioxide. The scrubber makes a gas that mostly consists of hydrogen and nitrogen in a 3:1 ratio, this stream is then heated and pressurized before being sent to the ammonia production reactor. After the ammonia reactor a cooler/separator condenses the ammonia and sends it to a buffer tank, while the non-converted hydrogen and nitrogen is recirculated back to the reactor. The produced ammonia is continuously pumped from the buffer tank to two larger storage tanks. The site produces around 44 000 tonnes of ammonia yearly. The process flow diagram can be seen in appendix A.5, a site map and for a satellite picture of the site together with the surrounding area see appendix A.6.

3.1.2 Scenarios

The majority of the identified scenarios are generic and have been taken from the BEVI risk manual. In table 3.1 these scenarios are listed outlining the scenario category, the relevant equipment on the site and the number of scenarios.

Category	**Relevant equipment**	**Number of scenarios from BEVI**
Pressurized storage tank, aboveground	Buffer tank, 2 product tanks, LPG tank	3
Pipelines	Methane pipeline, pipeline from buffer tank to product tank, pipeline from scrubber to heater	2
Reactor vessel and process vessel	Synthesis gas reactor, ammonia reactor, reformer	3
Pumps and compressors	3 pumps, 3 compressors	2
Heat exchangers and condensers	1 heater, 1 condenser	3
Pressure relief device	4 safety relief devises; one each for the product tank, synthesis gas reactor and ammonia reactor	1
Transport units	Train with 5 wagons	2
Loading activities	One loading hose for the train wagons	2

Table 3.1: BEVIs categories for the generic scenarios, the relevant equipment found in the fictitious site and the number of scenarios per equipment

For the pipelines the ones chosen were the ones that either were very long or crossed a road and therefore increased the frequency of the scenarios. All other pipelines were short and did not contain any substances that were significantly more hazardous, leading to them not contributing more then the selected pipelines.

The specific scenarios that were found through the HAZID were two run-away reactions in the synthesis gas reactor and ammonia reactor and also a BLEVE for the LPG tank. In figure 3.1 the event tree for the BLEVE is shown, this is taken from BEVI, [6].

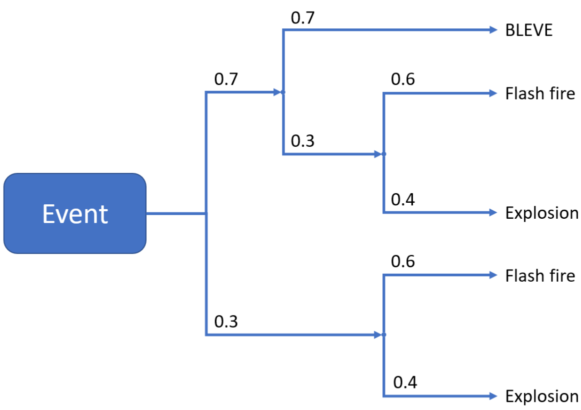


Figure 3.1: Event tree for a BLEVE aboveground, [6]

3.1.3 Assumptions

Throughout the course of a QRA assumptions are required both stemming from the models and any data gaps encountered during the calculations. This section aims to provide clarity regarding some of the assumptions made in this QRA, ensuring that readers have a comprehensive understanding of the sources of information utilized.

For the specific scenarios, the frequency of the runaway reaction proved to be to challenging, resulting in using the conservative method and estimating it to 1×10^{-3} to ensure that the risk is not undervalued. The frequency for the BLEVE scenario was sourced from BEVI [6].

The probability of both immediate and delayed ignition was calculated for ammonia. This decision was based on the observation that, in the results obtained from RiskCurve, the predominant hazard in all pure ammonia scenarios was its toxicity. Considering that the standard probability of immediate ignition was set to 0.8 and for delayed ignition 0.2 a lower probability should have a significant effect on these scenarios.

Many of the inputs was given by IPS and AFRY as part of the design of the plant and little complement was needed. Some values needed were missing and required estimation. This was accomplished by referencing other parts of the process with similar conditions in terms of substances, temperature, and pressure values, allowing for the estimation of the missing data. Notably, weather conditions significantly impact the resulting risk. Although a wind rose was provided, stability class and wind speeds were sourced from IPS recommendations for instances where such data is unavailable.

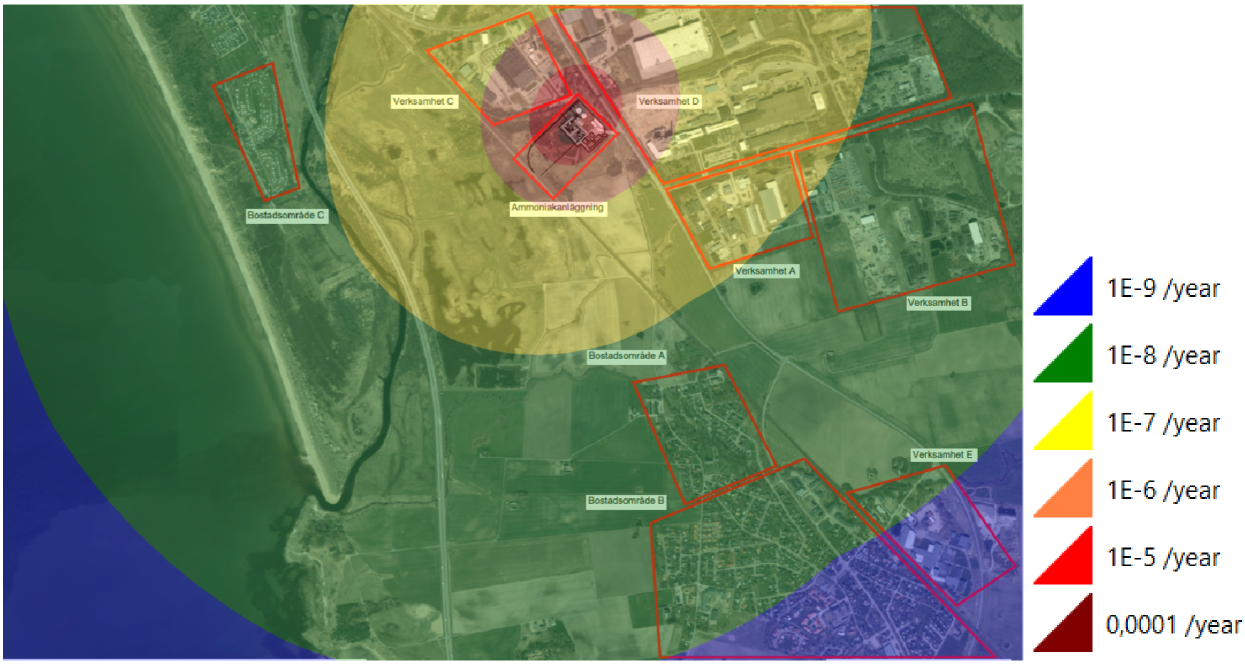
3.1.4 Results

The following figures show the resulting risk assessment from the frequency and consequence analysis, first in the form of individual risk that states the probability of one person dying at a set distance from the risk source. Next, the societal risk is presented, illustrating the frequency of one or more fatalities given the population of the surrounding area.

In figure 3.2 the individual risk contours are shown for all scenarios combined. IPS:s states that an individual risk exceeding 10^{-6} is a non-tolerable risk, this is represented by everything inside the red and orange region. The tolerable risk level is 10^{-8} and is represented by the blue color. Hence, the yellow and green regions are in the ALARP region.

In the non-tolerable region there is a portion of 2:nd persons in the region, meaning people working in neighboring sites. Half of operation C is within the non tolerable region as well as a partial portion of operation D. This is undesirable as this affects people outside the fictitious site and risk reductions are needed.

The ALARP region envelops the majority of the surrounding area, all of the residential areas are in this region and the rest of the other operations A, B and C. This all concludes to a non-negligible risk level. Therefore some form of risk reducing mitigation has to be considered to further decrease the ALARP region.



(a) Individual risk curve **(b)** Legend

Figure 3.2: a) Individual risk curve for all scenarios, both generic and specific. b) Is the legend for the different contours.

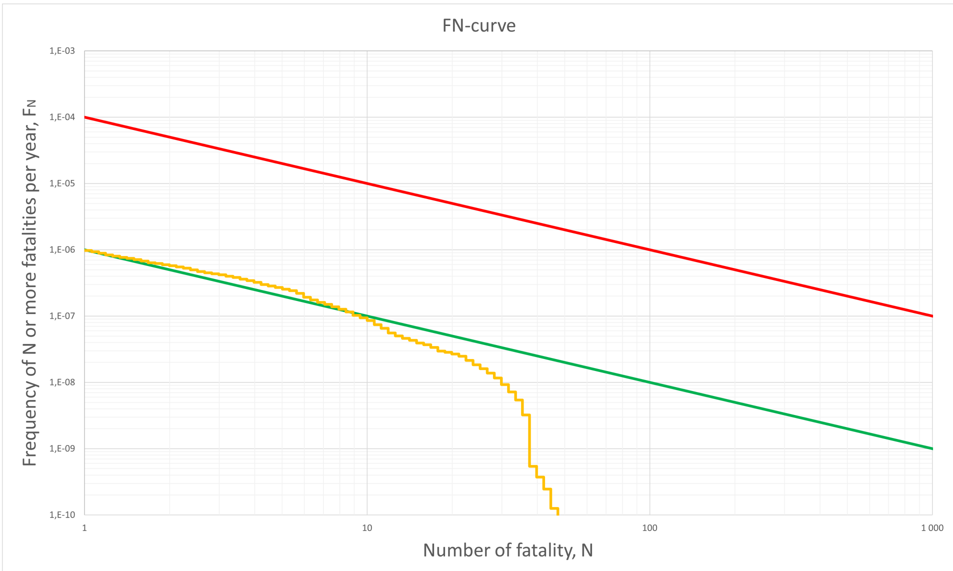


Figure 3.3: The Societal risk diagram for the accumulative risk with all scenarios.

In figure 3.3 the societal risk for all scenarios combined is shown. In the diagram the upper criteria limit is never exceeded. The risk is close to the lower criteria limit but slightly above. There are a lot of unpopulated areas. This can explain why the societal risk is low. New developments with large populations near the plant in the future will increase the societal risk so that it may become more of a concern. From looking at the shape of the line, being that it is more elongated on the x-axis, this indicates that the probability of the scenario occurring is low, but that the consequences have great impact [5]. This might warrant some risk reducing mitigation as the consequence is high.

As this is a for a site that is yet to be build it is important that any mitigation or risks are highlighted and ensured that they are included in the final production as well as that they are maintained.

3.1.5 Uncertainties

The uncertainties that arises during a QRA was handled in the way that IPS recommends, by doing a sensitivity analysis. It was concluded that the four most prominent parameters that could affect the results were the filling degree, the surrounding environments topography, the populations data and the failure frequency of pumps and compressors. For the population data every value was either halved or doubled, including the number of people and the time spent at the region. The frequency of pumps and compressors where chosen as the pumps are the prominent contributors of the estimated risk levels.

Parameter	Divided by 2	Original value	Multiplied by 2
Filling degree [%]	40	80	100
Topography	Open flat terrain;...	High crops;...	City center ...
Population data	Operation A: People 37.5, Time 20 h/week	Operation A: People 75, Time 40 h/week	Operation A: People 150, Time 80 h/week
	Operation B: Day People 10, Time 5 h/week; Night People 20, Time 48 h/week	Operation B: Day People 20, Time 10 h/week; Night People 40, Time 96 h/week	Operation B: Day People 40, Time 20 h/week; Night People 80, Time 168 h/week
	Operation C, workers: People 12.5, Time 30.5 h/week	Operation C, workers: People 25, Time 61 h/week	Operation C, workers: People 50, Time 122 h/week
	Operation C, visitors: People 25, Time 1.5 h/day	Operation C, visitors: People 50, Time 3 h/day	Operation C, visitors: People 100, Time 6 h/day
	Operation D: Day People 50, Time 15 h/week; Night People 15, Time 48 h/week	Operation D: Day People 100, Time 30 h/week; Night People 30, Time 96 h/week	Operation D: Day People 200, Time 60 h/week; Night People 60, Time 168 h/week
	Residential area A: Day People 37.8, Night People 54	Residential area A: Day People 75.6, Night People 108	Residential area A: Day People 151,2, Night People 216
	Residential area B: Day People 114.5, Night People 148.5	Residential area B: Day People 229, Night People 297	Residential area B: Day People 458, Night People 594
	Residential area C: Day People 19, Night People 27	Residential area C: Day People 38, Night People 54	Residential area C: Day People 76, Night People 108

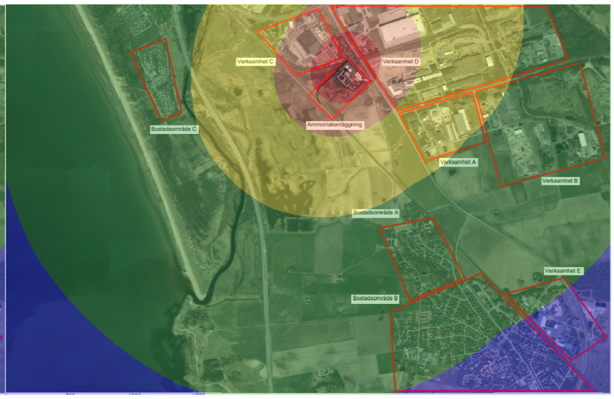
Table 3.2: The input for RiskCurve for the different values in the sensitivity analysis

Table 3.2 describes how the parameters were changed and the different values used in Riskcurve. The following figures depicts the new individual contours resulting from the changed parameters.

(a) Population data halved

(b) Population data doubled

(c) Frequency of pumps halved



(d) Frequency of pumps doubled

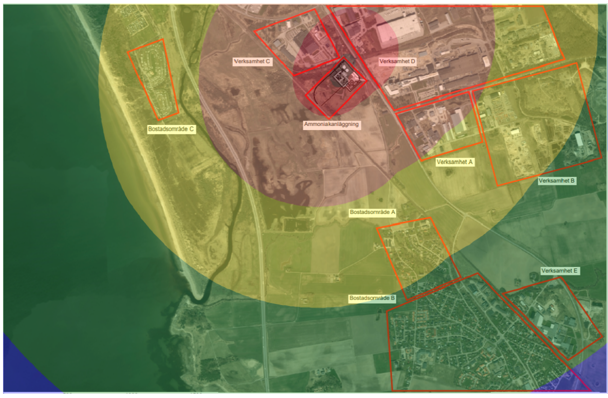
Figure 3.4: The individual risk from the sensitivity analysis regarding the population data and the frequency of the pumps and compressors.

From figure 3.4 the changes from the two different values for the population data and the pumps/compressors frequency has changed. For the changes in the population data it is seen that there is no change. This stems from that individual risk is not based on the population data but the distance from the leak source. The reason to include the population stems from the fact that the number of people directly influence the societal risk.

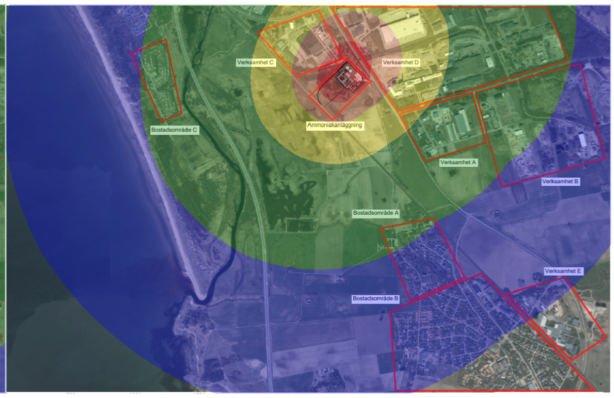
That the change in frequency does not result in larger individual risk is reassuring as they contribute a majority to the total risk assessment. This is the reason for including the failure frequency of pumps and compressors specifically as the other components did not contribute as much.

(a) Filling degree 40 %

(b) Filling degree 100 %



(c) Topography "Open terrain;..."

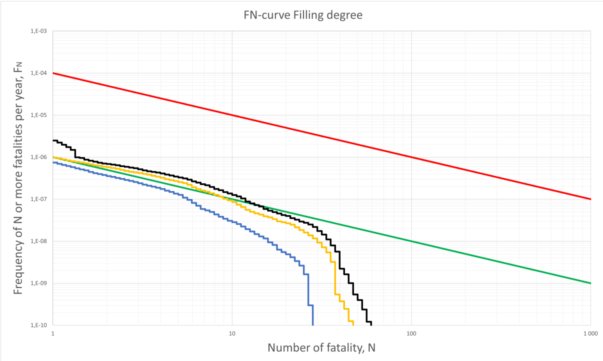


(d) Topography "City center..."

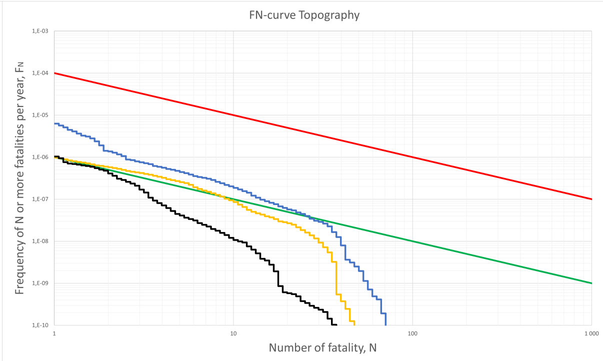
Figure 3.5: The individual risk from the sensitivity analysis regarding the filling degree and the topography.

When looking at figure 3.5 regarding the filling degree and topography there are clear differences between each change in parameter. For the filling degree the risk is much lower when halved, this is reasonable as there is less substances to be released. But, when it is set to 100 % there is a notable change of the non-tolerable region as it increases. The way the amount in the vessels are relevant depends on what type of final outcome is the most dangerous. When decreasing the filling degree more of the liquid is evaporated into gas, resulting in more fuel for potential fires. But as ammonia is the biggest contributor to the risk and this has a low probability of ignition it mostly means that lesser amount is released. It can though be seen that with a higher filling degree the individual and societal risks have increased.

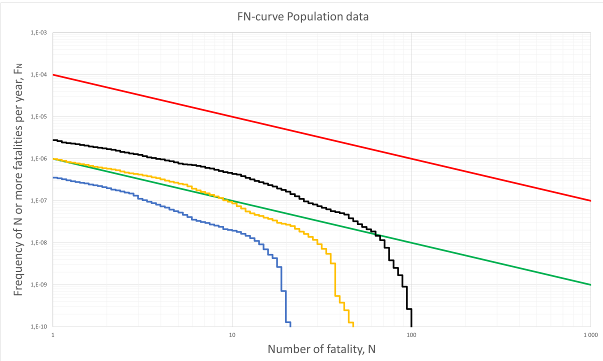
When the topography is varied the instance where the ground is said to have more obstructions a significant decreases of the risk is seen, but not a complete reduction of risk as it still crosses over onto other operations. However, as the topography is set to have a flat ground the spread from ammonia toxic cloud becomes larger resulting in a much higher risk. Both the not-tolerable risk and ALARP region has increased significantly, and is now covering majority of the map. Following the individual contours is the societal risk diagram from the four different parameters varied. It was important to include topography in the sensitivity analysis as when looking at the geographical nature of the area there are different heights of obstructions. To the far left is a large body of water, this is flat and needs to be included as the wind directions can be towards the water and then the spread of the leaks will change.



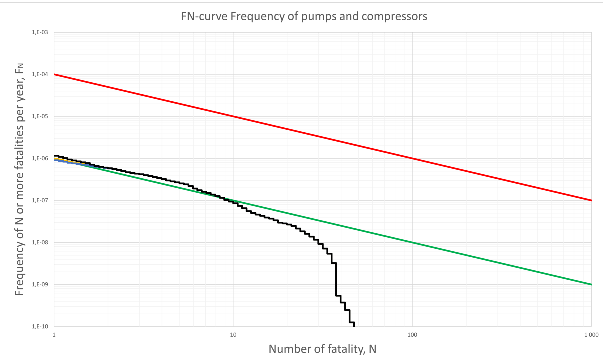
(a) Filling degree



(b) Topography



(c) Population data



(d) Frequency of pumps

Figure 3.6: The combined societal risk results from the sensitivity analysis for the three relevant parameters

The yellow line in figure 3.6 represents the societal risk for the original values, the blue represents the halved values and the black line represents the doubled values of the parameter. From the societal risks it is seen that the upper criteria limit is never exceeded therefore non of the parameters are deemed to be sensitive. However both in the topography and population data instances there is a significant increase. This falls in line with what was observed from the individual risk and show that the two most sensitive parameters are the topography and the population data.

From the sensitivity analysis it is concluded that the population data and the topography of the surrounding area are the two most influential parameters on the resulting risk assessment. For this QRA the populations data was specified ahead of time. For the topography, the exact location on Earth is not given hindering the student to gather more exact geographical information of the area than what can be deduced from the map of said area.

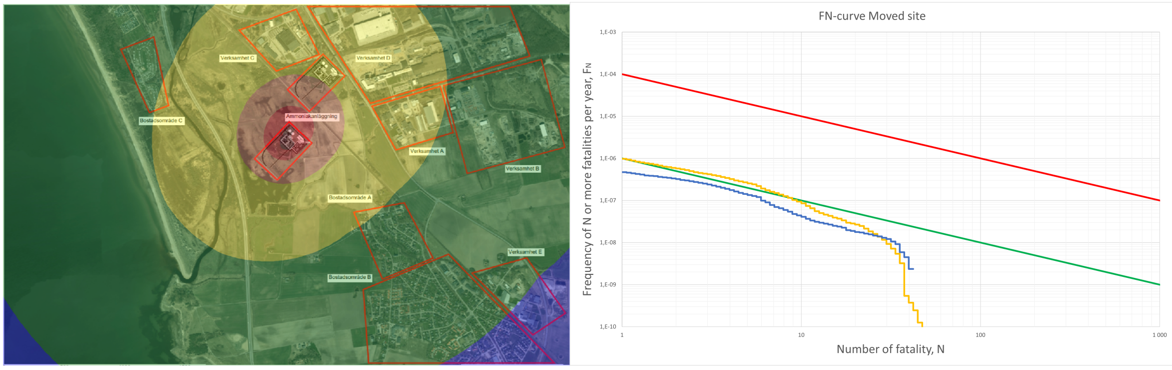
3.1.6 Conclusions of QRA

The individual risk is high, while the societal risk is close or under the lower criteria level. There is need for risk reducing measures mainly based on the individual risk, but also on the risks that have large consequence concluded from the societal risk diagram.

3.1.6.1 Recommendations

From the results it is recommended to implement some risk reduction measures. As the site is yet to be built it is possible to implement mitigations that does not effect the existing design.

The first recommendation is to consider alternative locations for the site, with less populated areas. As the non-tolerable region crosses over to other operations it is best to move the site to a position where the non-tolerable region does not cross over anything else.

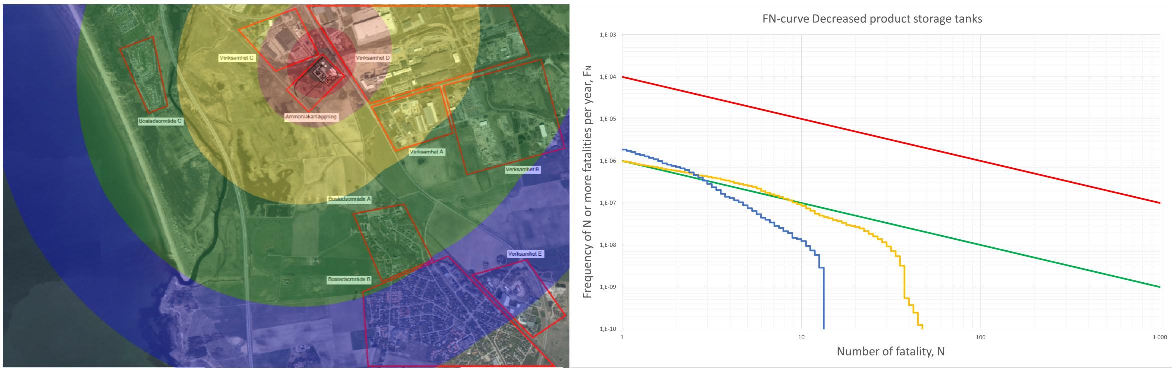


(a) Individual risk **(b)** Societal risk

Figure 3.7: The individual risk and societal risk for when the entire site is moved further down.

From figure 3.7 it can be seen that by moving the site now the non-tolerable region of the individual risk does not overlap with region of populations. It is also evident that the societal risk decreases as well.

Secondly as the largest risks lies with the formation of toxic ammonia clouds, so reducing the product storage tanks to smaller vessels would help in reducing the risk. This is made by ensuring that the released content is less. Today the two tanks are set to 4000 m^3 but for safety reasons it would be better to have eight 1000 m^3 vessels instead.



(a) Individual risk **(b)** Societal risk

Figure 3.8: The individual risk and societal risk for when the ammonia storage tanks have a volume of 1000 m^3.

The individual risk shown in figure 3.8 has a slightly smaller non-tolerable risk region compared to the original individual risk. The ALARP region has also significantly reduced its size. The societal risk shows a increase for smaller amounts for fatalities but the maximum number has decreased, leading to the conclusion that the consequences have decreases.

3.2 Evaluation

In the following sections the different evaluation structures used are presented with the results from performing a QRA and reflecting on the usefulness of said QRA report and how the IPS guideline work in this practical application.

3.2.1 The purpose of the guidelines

The IPS guideline is divided into two separate parts. Both of the parts states that the overall purpose is to standardize the procedures and the utilization of QRA in Sweden. Additionally, the guideline also states its endeavor to create a foundation for more serious work using QRA methodology in Sweden. This purpose is clearly explained in the introductory section of both parts.

Part 1 is intended for readers without prior knowledge of QRA or necessarily process industries, they are the individuals reading the completed report and forming decisions regarding safety procedures. This part provides a general overview of QRA methodology, including when and how it should be implemented. It also provides some background on the situation in Sweden and two comparative countries Netherlands and Norway.

Part 2 targets the practitioners performing the QRA. It is structured for the practical application of QRA, detailing the methodology, providing guidance on how to document each stage comprehensively and how to properly illustrate the results for easy comprehension. Part 2 is also the part that has been further evaluated based on the criteria.

3.2.2 Criteria for evaluation

For the evaluation, each of the criteria in Table 2.9 has been considered for each chapter in the IPS guideline (QRA Part 2). Comments about each chapter and the most relevant criteria are noted in Table 3.3 below.

Chapter	Most relevant criteria	Less relevant criteria
Inledning (Introduction)	Completeness, Consistency, Transparency, Practicability, Robustness	Accuracy, Validity, Resilience
Scenarier (Scenarios)	Accuracy, Completeness, Consistency, Validity, Transparency, Practicability	Resilience, Robustness
Frekvensanalys (Frequency analysis)	Accuracy, Validity, Transparency, Resilience	Consistency, Completeness, Practicability, Robustness
Modellering av källstyrka (Modeling of source strength)	Consistency, Validity, Transparency	Accuracy, Completeness, Resilience, Practicability, Robustness
Konsekvensanalys (Consequence analysis)	Accuracy, Completeness, Consistency, Validity, Transparency, Resilience	Practicability, Robustness
Modellering/ beräkning av exponering och skador (Modeling/Calculations of exposure and damages)	Accuracy, Consistency, Validity, Resilience	Completeness, Transparency, Practicability, Robustness
Beräkning av risk (Calculations of risk)	Consistency, Validity, Transparency, Resilience	Accuracy, Completeness, Practicability, Robustness
Värdering av risk (Assessment of risk)	Consistency, Validity, Transparency, Robustness	Accuracy, Completeness, Resilience, Practicability
Hantering av osäkerhet (Handling uncertainties)	Consistency, Validity, Transparency, Practicability, Robustness	Accuracy, Consistency, Resilience
Kvalitetssäkring (Quality assurance)	Accuracy, Validity, Transparency, Practicability, Robustness	Completeness, Consistency, Resilience

Table 3.3: The chapters from IPS guideline for QRA part 2 and their relevance to the criteria

3.2.2.1 Chapter "1 Inledning"

As this is the introducing chapter of the guidance it introduces the many different parts of the rest of the chapters. It also specifies the scope of what IPS recommends to be in a QRA and many of the relevant terminology used. This chapter is very well done as it sets up the reader for the coming chapters and their more in depth explanations.

3.2.2.2 Chapter "2 Scenarier"

As the hazard identification is the foundation for the entire QRA, this chapter is very important. The majority of the scenarios used in the calculations comes from the generic causes, BEVI, but to incorporate them all it was necessary to understand and have the information about the different equipment used and any additional components.

The recommendation of having e.g. a HAZOP done before beginning on QRA would help find all specific causes and streamline the process of identifying all of the scenarios.

Something that was found difficult as a novice was that there is no clear end to when sufficient scenarios are identified. The guideline does state that it is an iterative process and that additional scenarios can be added along the way when they are identified further into the analysis. This problem is more evident when realistic sites are analyzed and the complexity of the site is increase leading to a increase in the number of scenarios included. But this study used a greatly simplified process leading to not having these concerns. But when QRA:s are performed normally there are clear objectives and time restraints that help navigate the identification process.

3.2.2.3 Chapter "3 Frekvensanalys"

When performing the frequency analysis much of the data was taken from BEVI, as recommended in the IPS guideline, expediting the process. It was decided that the ignition probability for pure ammonia was going to be calculated and not to use the standard values. How to perform the calculations was shown for three different cases depending on the hazardous chemical. The equations and correlations needed were clearly shown. If the data had not been predetermined then the guidance explained how and were to obtain the data. This also helped understand the data used as one can see how to restructure it to be used in the calculations later.

3.2.2.4 Chapter "4 Modellering av källstyrka"

As much of the calculations used RiskCurve there was not much need for the practitioner to calculate, other than to ensure the input was correct. It was not possible to find the actual equations that RiskCurve used for these calculations to ensure that they are using the same as is recommended by the guideline.

3.2.2.5 Chapter "5 Konsekvensanalys"

Similarly to the modeling of source strength much of the work was performed by RiskCurve. The student confirmed that the models available to select were the ones that IPS guidance recommended. RiskCurve works somewhat as a black box, meaning that the actual calculations cannot be seen or necessarily changed.

3.2.2.6 Chapter "6 Modellering/beräkning av exponering och skador"

In the IPS guidance there are vulnerability criteria for toxic gas, gas cloud fire, BLEVE, fires and explosions. When using RiskCurve this was ensured to be same or it was changed to the IPS recommendation.

3.2.2.7 Chapter "7 Beräkning av risk"

Calculating the risk was entirely done by RiskCurve. RiskCurve has a validation document ensuring that it is acceptable to use it for this purpose. In the guidance there are the necessary equations for calculating it manually ensuring that the practitioner can understand how the values are calculated.

3.2.2.8 Chapter "8 Värdering av risk"

As the assessment of risk can become subjective the need for clear and precise guidance with what is the risk levels and the reasoning behind it are instrumental. The risk levels used are similar to what other guidances use for this assessment, leading to a possible comparability between different QRA reports even if they are done by different practitioners. There are some practical examples giving the practitioner support when studying their own results, but some more examples with a larger variability in different combinations of individual risk contours and their societal risk diagrams would improve and show how one should reason.

3.2.2.9 Chapter "9 Hantering av osäkerhet"

When handling the uncertainties the IPS guidance give a clear method for performing a sensitivity analysis. For a novice practitioner the first step in identifying the influential parameters can be difficult and result in a large number of parameters. This is not necessarily bad but will take longer time compared to an experienced practitioner having a more condensed list to analyze. The way to interpret the resulting variations can be subjective and the guidance does not give a practical example of how the results can look for different situations.

3.2.2.10 Chapter "10 Kvalitetssäkring"

The quality assurance is extremely important for the QRA report as it is used for decisions regarding safety measures. This chapter clearly states what roles have what responsibility toward the QRA. It also gives an example of how to plan the process of the QRA.

For this work regular workshops with three experts were held on a regular basis and a thorough cross-examination of all of the simulations was also conducted to ensure that the right values and assumptions were used.

4

Conclusions

In conclusion, the IPS guidance for Quantitative Risk Assessment (QRA) Part 2 offers a comprehensive and systematic framework for practitioners. It covers all critical components of the QRA methodology, from the initial definition of scope and relevant terminology to detailed procedures for hazard identification and scenario development. Emphasis is placed on the importance of preliminary studies, such as HAZOP, to ensure a thorough and efficient hazard identification process.

The guidance provides clear instructions for frequency analysis, including necessary equations and methods for handling both generic data and new data acquisition. It discusses the modeling of source strength and consequence analysis, highlighting the role of software such as RiskCurve in automating these complex calculations while ensuring the accuracy of inputs.

Moreover, the guidance addresses the modeling of exposure and damage, providing specific vulnerability criteria and ensuring consistency with IPS recommendations when using RiskCurve. The risk calculation section reassures practitioners of the reliability of RiskCurve through its validation documentation, while also offering manual calculation methods for deeper understanding.

The guidance on risk assessment emphasizes the need for clear, precise risk levels and justifications to ensure comparability and transparency across different QRA reports. It also provides a methodology for handling uncertainties through sensitivity analysis, acknowledging the challenges faced by novice practitioners in identifying key parameters and interpreting results without practical examples.

Lastly, the importance of quality assurance is emphasized, delineating roles and responsibilities and offering a structured approach to planning the QRA process. Overall, the IPS guidance equips practitioners with the necessary tools and knowledge to conduct thorough, reliable, and transparent QRA:s, fostering safety and risk management in various industrial contexts.

While the guidance provides a robust framework there are some areas in need of further development. One of this areas are the hazard identification step. For a novice it can be a daunting step both in the way of it being the back bone of the entire QRA but also due to the difficulty in knowing if enough scenarios have been identified. With this it means that the practitioner can always identify more scenarios making it more complex. This is not necessarily a problem for when the guidance is applied to real sites and situations as then there are always clear objectives with the QRA report and some time restraints which both become limitations for when performing the QRA. A secondary area that could be improved upon is that there are some calculation examples but in my opinion there could be more. For practitioners not using QRA software such as RiskCurve it would be beneficial to provide more calculation examples that they can follow.

To summarize, the IPS guidelines represent a significant step towards the standardization of QRA procedures in Sweden. They provide a comprehensive and flexible framework that, while needing some refinements, have the potential to improve the quality and consistency of QRA reports. Future revisions should focus on offering more detailed guidance on result interpretation, such as how to use the QRA for assessing the merits of possible risk reduction options, and more practical examples to give the practitioner support in understanding the calculations better. Such enhancements will further solidify the guidelines' role in promoting rigorous and standardized QRA practices in Sweden.

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A

Appendix 1

A.1 Population data

Area	Number of people
Operation A: Office an warehouse	Work hours: Office hours; 75 employees
Operation B: Small industry	Work hours: Office hours and afternoon, nights and weekends; 20 and 10 employees
operation C: Trade in rare goods	Work hours: weekday 10-19, weekend 10-18; 25 employees; 50 visitors per day
Operation D: Chemistry industry	Work hours: office hours and afternoon, nights and weekends; 100 and 30 employees
Operation E: Office and warehouse	Work hours: Office hour; 30 employees
Residential area A	40 villas ⇒ Total 108 people
Residential area B	100 villas and 30 apartments ⇒ Total 297 people
Residential area C	20 townhouse ⇒ Total 54 people

Table A.1: Population data of the surrounding area of the site given by IPS and AFRY

Time	Inside	Outside
Day	0.93	0.07
Night	0.99	0.01

Table A.2: Distribution of people inside and outside depending on time of day, [6]

Type of Building	People distribution
Villas	2.7 people per household
Apartments	1.9 people per household
Office	1 person per 30 m^2 BTA
Storage	1 person per 200 m^2 BTA
Hotel	1.5 person per room

Table A.3: Data for people distributed in various types of buildings, [5]

A.2 Predetermined process conditions

Stream	Composition [mole %]	Flow [kmole/h]	Flow [kg/h]	Dimension [mm]	Pressure [bar]	Temperature [C]
1	100 % CH4	150	2400	100	30	10
2	50 % H2O 50 % CH4	300	5100	200	30	10
3	45 % H2 20 % CO 15 % N2 20 % H2O	1000	14200	200	30	700
4	45 % H2 15 % CO 15 % CO2 15 % N2 10 % H20	1000	17500	200	30	500
5	45 % H2 15 % CO 15 % CO2 15 % N2 10 % H20	1000	17500	150	100	500
6	75 % H2 25 % N2	600	5000	200	100	200
7	75 % H2 25 % N2	600	5000	150	200	450
8	34 % NH3 50 % H2 16 % N2	900	10000	200	200	450
9	100 % NH3	300	5000	100	10	25
10	75 % H2 25 % N2	600	5000	100	10	25
11	75 % H2 25 % N2	600	5000	150	10	25
12	100 % NH3		-	-	10	25
13	100 % NH3	1700	29200*	80	10	25

Table A.4: The predetermined process conditions given by AFRY and IPS, the numbering is based on figure A.5.
* Represents the filling speed of the train cargo.

The vessel	Diameter [m]	Height [m]	Bund diameter [m]	Bund height [m]
Buffet tank	8	4	12	2
Product tank	25	8	60	3
Primary reformer	4	9	-	-
Secondary reformer	3	6	-	-
Synthesis gas reactor	4	8	-	-
Scrubber	2.5	10	-	-
LPG tank	2.5	10	-	-
Ammonia reactor	3	12	-	-
Loading zone for train cargo	-	-	10	10

Table A.5: The dimension for the vessels and their respective bunds.

The safety release valves on the product storage tanks have a maximum outflow of 10 kg/s and for the two reactor it is set to 15 kg/s. In case of leaks around the loading zone there is a emergency-shut-off system that closes the pipe in 2 min (120 s). This is accounted for in the loading activities, and the three pumps after the cooler/separator, scenario number 6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 10.1, and 10.2 from table A.6.

A.3 Scenarios for RiskCurve

Nr.	**Cause/Scenario**	**Frequency** [year^{-1}]
1.1	Buffet tank, instantaneous release of entire contents	5e(-07)
1.2	Buffet tank, release of entire content in 10 min	5e(-07)
1.3	Buffet tank, continuous release of content from a hole with an effective diameter of 10 mm	1e(-07)
1.4	Product tank, instantaneous release of entire contents	5e(-07)
1.5	Product tank, release of entire content in 10 min	5e(-07)
1.6	Product tank, continuous release of content from a hole with an effective diameter of 10 mm	1e(-07)
1.8	LPG tank, instantaneous release of entire contents	5e(-07)
1.9	LPG tank, release of entire content in 10 min	5e(-07)
1.10	LPG tank, continuous release of content from a hole with an effective diameter of 10 mm	1e(-07)
1.11	BLEVE LPG tank	2.45e(-07)
3.1	Methane to site, rupture in the pipeline (70 m)	3e(-07)
3.2	Methane to site, leak with an effective diameter of 10% of the nominal diameter	2e(-06)
3.3	NH3 to product tank from buffet, rupture in the pipeline (71 m)	3e(-07)
3.4	NH3 to product tank from buffet, leak with an effective diameter of 10% of the nominal diameter	2e(-06)

3.5	Pipe between scrubber and heater, rupture in the pipeline (71 m)	3e(-07)
3.6	Pipe between scrubber and heater, leak with an effective diameter of 10% of the nominal diameter	2e(-06)
4.1	Synthesis gas reactor leak, instantaneous release of entire contents	5e(-06)
4.2	Synthesis gas reactor leak, release of entire content in 10 min	5e(-06)
4.3	Synthesis gas reactor leak, continuous release of content from a hole with an effective diameter of 10 mm	1e(-04)
4.5	Ammonia reactor, instantaneous release of entire contents	5e(-06)
4.6	Ammonia reactor, release of entire content in 10 min	5e(-06)
4.7	Ammonia reactor, continuous release of content from a hole with an effective diameter of 10 mm	1e(-04)
4.8	Reformer leak, instantaneous release of entire contents	5e(-06)
4.9	Reformer leak, release of entire content in 10 min	5e(-06)
4.10	Reformer leak, continuous release of content from a hole with an effective diameter of 10 mm	1e(-04)
4.11	Run-away reaction synthesis gas reactor	1e(-03)
4.12	Run-away reaction ammonia reactor	1e(-03)
6.1	Pump after buffer tank, catastrophic failure with 2 emergency stop	9.9e(-05)
6.1	Pump after buffer tank, catastrophic failure without 2 min emergency stop	1e(-06)

6.2	Pump after buffer tank, leak with an effective diameter of 10% of the nominal diameter with 2 min emergency stop	4.36e(-03)
6.2	Pump after buffer tank, leak with an effective diameter of 10% of the nominal diameter without 2 min emergency stop	4.4e(-05)
6.3	Pumps after the product tank (2#), catastrophic failure with 2 emergency stop	9.9e(-05)
6.4	Pumps after the product tank (2#), leak with an effective diameter of 10% of the nominal diameter with 2 min emergency stop	4.36e(-03)
6.5	Pumps after the product tank (2#), catastrophic failure without 2 min emergency stop	1e(-06)
6.6	Pumps after the product tank (2#), leak with an effective diameter of 10% of the nominal diameter without 2 min emergency stop	4.4e(-05)
6.7	Compressor 1 after synthesis gas reactor, catastrophic failure	1e(-04)
6.8	Compressor 1 after synthesis gas reactor, leak with an effective diameter of 10% of the nominal diameter	4.4e(-03)
6.9	Compressor 2 after the heater before ammonia reactor, catastrophic failure	1e(-04)
6.10	Compressor 2 after the heater before ammonia reactor, leak with an effective diameter of 10% of the nominal diameter	4.4e(-03)
6.11	Compressor 3 after the cooler before the ammonia reactor, catastrophic failure	1e(-04)

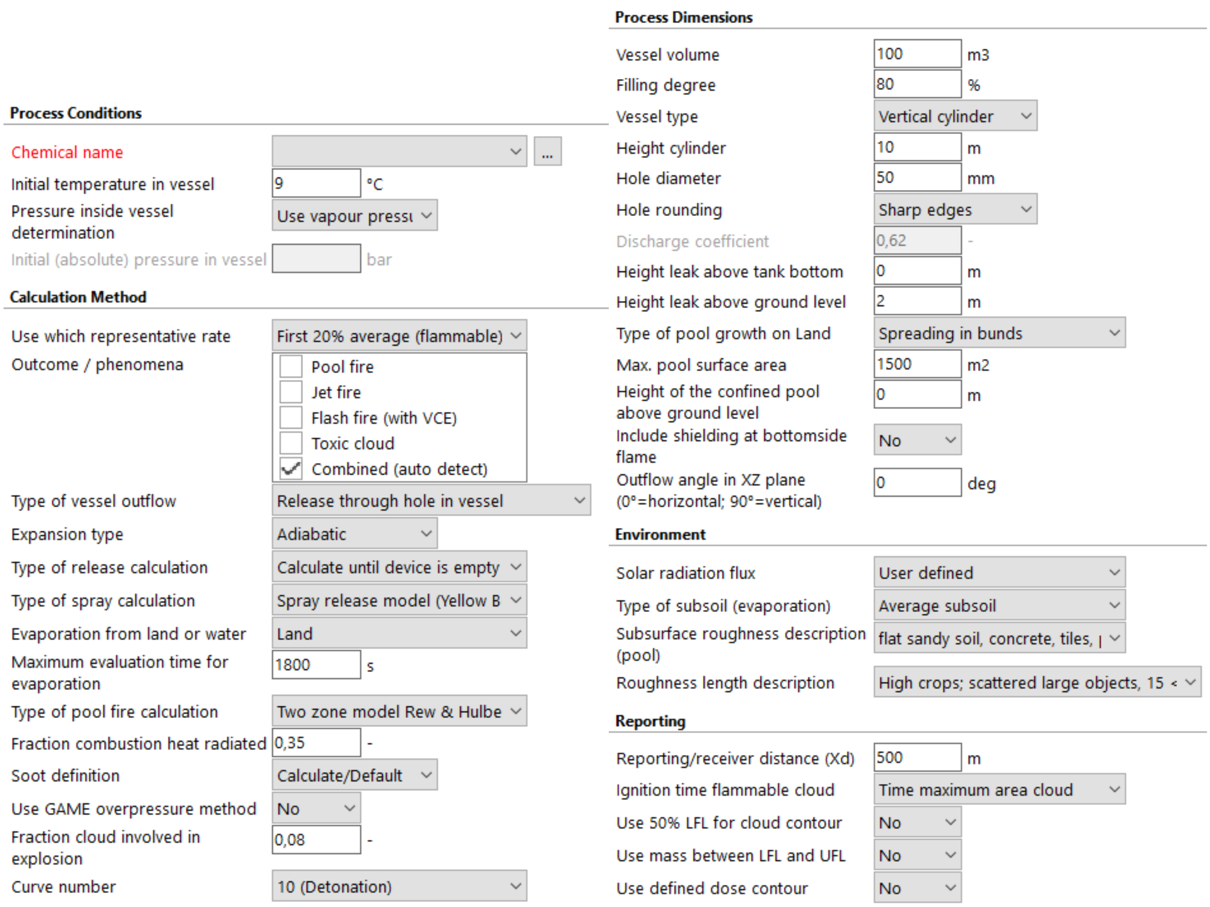
6.12	Compressor 3 after the cooler before the ammonia reactor, leak with an effective diameter of 10% of the nominal diameter	4.4e(-03)
7.1	Heater between the scrubber and compressor 2, instantaneous release of entire contents	5e(-05)
7.2	Heater between the scrubber and compressor 2, release of entire content in 10 min	5e(-05)
7.3	Heater between the scrubber and compressor 2, continuous release of content from a hole with an effective diameter of 10 mm	3e(-03)
7.4	Cooler after ammonia reactor, instantaneous release of entire contents	5e(-05)
7.5	Cooler after ammonia reactor, release of entire content in 10 min	5e(-05)
7.6	Cooler after ammonia reactor, continuous release of content from a hole with an effective diameter of 10 mm	3e(-03)
8.1	Safety release valve of product tank (2#), outflow at the maximum outflow rate	2e(-05)
8.2	Safety release valve of synthesis gas reactor (2#), outflow at the maximum outflow rate	2e(-05)
8.3	Safety release valve of ammonia reactor (2#), outflow at the maximum outflow rate	2e(-05)
9.1	Leak from train cargo (5#), instantaneous release of entire contents	5e(-07)
9.2	Leak from train cargo (5#), release of entire contents from the largest connection	5e(-07)

10.1	Rupture of loading hose (31m) with 2 min emergency stop	3.96e(-06)
10.1	Rupture of loading hose (31m) without 2 min emergency stop	4e(-08)
10.2	Leak in loading hose with an effective diameter of 10% of the nominal diameter with 2 min emergency stop	3.96e(-05)
10.2	Leak in loading hose with an effective diameter of 10% of the nominal diameter without 2 min emergency stop	4e(-07)

Table A.6: Input scenarios for RiskCurve

A.4 Default values from RiskCurve 12.0.1

All of the data that was not provided was set to the default values that RiskCurve 12.0.1 gives. This data can be seen in figure A.1. The "Curve number" was ether set to 5 or 6 depending on if the chemicals were pure ammonia respective any other substance. For the scenarios simulating the emergency shut of system two settings were changed; "Type of release calculation" set to "Calculate until specified time" and then "Maximum release duration" set to 120 s.



(a) (b)

Figure A.1: The set default values for RiskCurve 12.0.1 for scenario "Liquefied Gas LOC Scenario Leak (G3) Set"

The reason for showing this type of scenario is that this one has the most input needed and the other scenarios have some variation of this but with less input.

A.5 Flowdiagram of the fictitious site

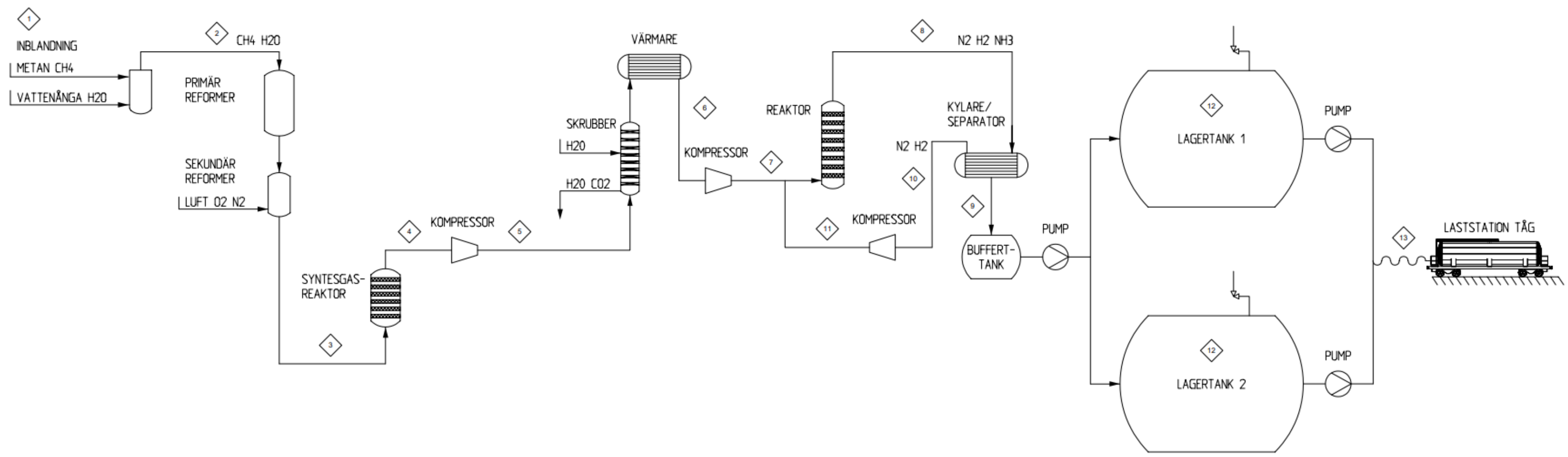


Figure A.2: Flow diagram of the fictitious site

A.6 The sites placement for the equipment and the surrounding area

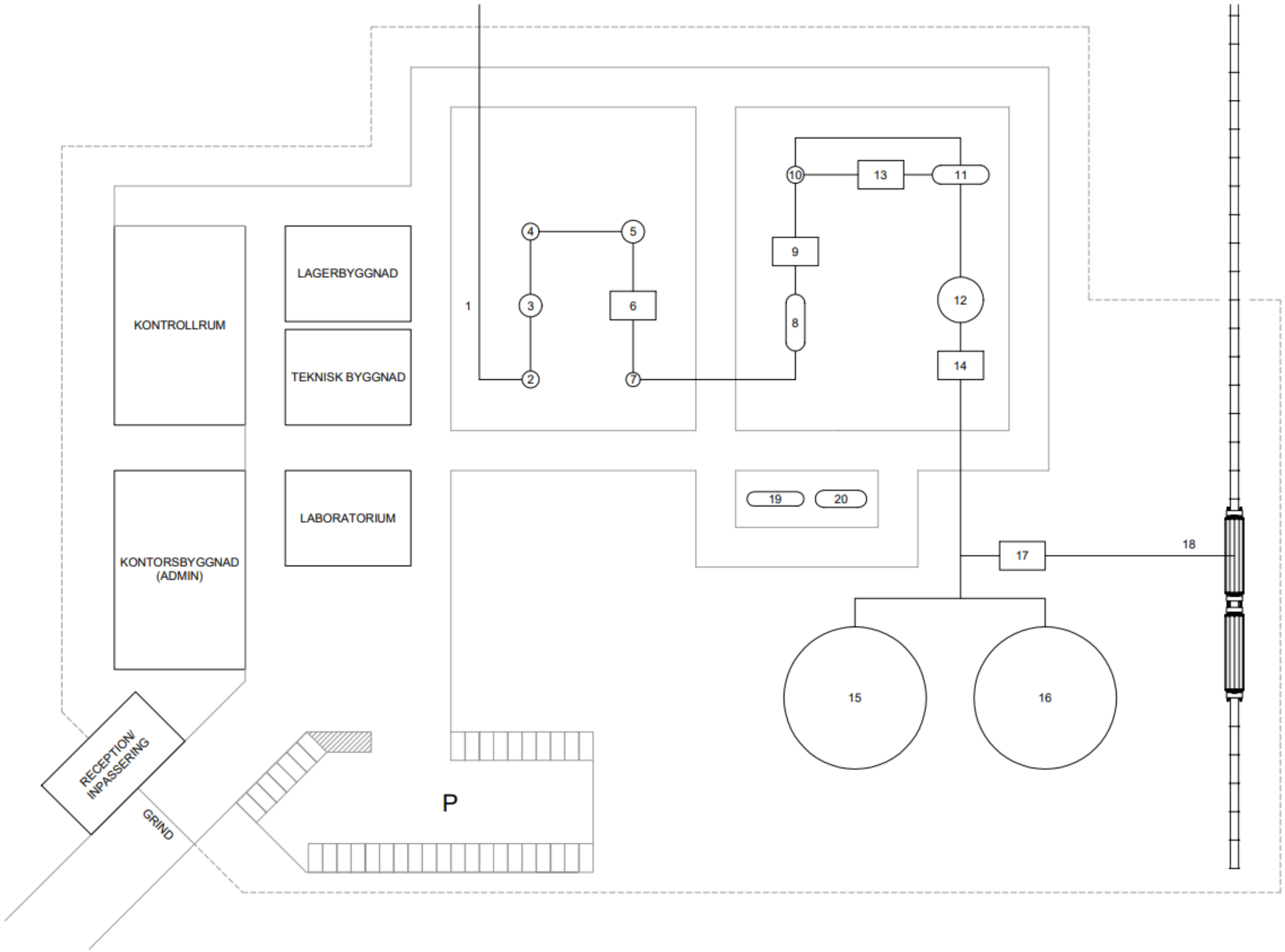


Figure A.3: Caption

Figure A.4: A satellite picture of the surrounding area for the fictitious site

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