"Recommendations for Improving the Use of Risk Matrices in Coarse Risk Analyses"

Esko Roos & Olga Helena Selitski | Division of Risk Management and Societal Safety| LTH | Lund University

“Recommendations for Improving the Use of Risk Matrices in Coarse Risk Analyses”

Esko Roos & Olga Helena Selitski

Lund 2023

“Recommendations for Improving the Use of Risk Matrices in Coarse Risk Analyses”

Esko Roos & Olga Helena Selitski
Number of pages: 123
Illustrations: 14

Keywords

Risk Matrix, Coarse Risk Analysis, Risk Assessment, Probability-Consequence Diagram, Guidance, Guidelines, Recommendations, Improvement.

Abstract

Risk matrices are tables with rows representing consequences, and columns representing frequencies. The risk matrix is considered a simple and convenient tool for visualizing risk. However, it has faced critique from the scientific community. Though risk matrices are extensively applied in practice for visualizing results from coarse risk analyses, there is limited research regarding guidance on its use. This thesis therefore aims to add to the currently limited guidance, considering suitability to practical applications. Recommendations for improving the use of risk matrices were identified through a litterature study, documentation study and interviews. From the literature study, 15 recommendations emerged. By studying the documentation and answers provided from interviews, six out of 15 recommendations were deemed practically suitable in the context of coarse risk analyses:

● Make users aware of the limitations of the matrix and highlight difficulties. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. View the tool with scepticism in mind.
● Make the risk matrix more comprehensible through a few simple visual improvements.
● Provide guidelines on the use of risk matrices for events with several consequence categories.
● Clarify how risks that have the same score/position in the matrix should be prioritized.
● Establish risk matrices with decision makers risk appetite in mind.
● Do not have a large variety of risk matrices within one company and industry, if there are not different risk appetites or clear motivations.

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund
Sverige

http://www.risk.lth.se

Telefon: 046 - 222 73 60

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se

Telephone: +46 46 222 73 60

Acknowledgements

We would like to extend our gratitude towards everyone who has been part of or facilitated the work with this thesis.

More specifically, we would like to thank the following:

Supervisor *Henrik Hassel* at the Department of Risk Management and Societal Safety, for his great support, availability and thorough repeated read-through of the content.

Associate Professor *Fredrik Åström* and librarian *Robin Gullstrand* for support with the citation and reference analyses.

Supervisor *Baris Arslan* at ORS Consulting for his support with the second part of the thesis.

Jan Nählinder Country Manager Sweden at ORS Consulting for provision of valuable contacts for the interviews.

HR/education responsible *Gitte Nählinder* at ORS Consulting for great support with improving the interview technique.

Interviewees *Esteban Bernechea Rojas, Carl Bonde, Richard Forss , Johan Ingvarson, Anders Jakobsson, Thomas Lackman, Mathias Nevrell, Morten Nilstad Pettersen, Thomas Solberg Fylking and Carsten Stegelmann* without whom the thesis would have been impossible to complete.

The ORS Consulting team for great office locations, company and additional risk matrices.

Last but not least, we would like to thank *Bosse* the cat for great company, distraction and cuteness on rough days.

Abbreviations

AHP - Analytical Hierarchy Process
ALARP - As Low as Reasonably Practicable
DMRA- Decision Matrix Risk Assessment
DRMA-Decision Risk Matrix
HAZID - Hazard Identification
HAZOP - Hazard and Operability
HIRA - Hazard Identification and Risk Assessment
HSE - Health and Safety Executive
IPL - Independent Protection Layer
ISO - International Organization for Standardization
LOPA - Layers of Protection Analysis
ORS - ORS Consulting
OSHA - Occupational Safety and Health Administration
PCDS - Probability Consequence Diagrams
PHA - Process Hazard Analysis
QRA - Quantitative risk assessment
SCRM - Supply Chain Risk Management
SRA - Society for Risk Analysis
SUA - Sequential updating approach

Definitions

Risk - The effect of uncertainty on objectives (ISO 3100) or combination of a probability of an event and its consequences (as described in Tehler, 2020)
Qualitative Risk Matrix- Purely qualitative descriptions of axes in the risk matrix
Semi-Quantitative Risk Matrix - One axis is purely qualitative whilst the other is quantitative (oftentimes with intervals). The risk score in this type of matrix may be of the format (10^{-6} - 10^{-4}) *Low.
Quantitative Risk Matrix - Both axes are purely quantitative.

Summary

Risk matrices are tables with rows representing consequences, and columns representing frequencies. They can be used for decision making about the acceptance of risk and prioritization of which risk should be addressed first (Duijm, 2015). They are also considered a tool for visualizing results from other risk analyses, such as for example a Hazard Identification (HAZID) study (Flage & Røed, 2012). The risk matrix has gained more and more popularity within the corporate world through the years, and been especially praised for its simplicity (Cox, 2008). As of now, they are widely used in practice and preferred by management when it comes to presenting risk (Ale et.al, 2014). One area of use is with regards to risk ranking of hazardous scenarios identified through coarse risk analyses (Baybutt, 2015). However, the risk matrix has been criticized with regards to not being able to support good decision making (Cox, 2008), simplifying something complex (e.g., representing consequence with one single value instead of a distribution of all possible consequences) (Flage & Røed, 2012), missing out on the full picture of the risk as only individual scenarios are visualized (ibid) and being subject to several biases (Duijm, 2015). As they are so widely used and considered convenient by many companies, simply replacing them with other tools might however be unrealistic (Flage & Røed, 2012).

Even though risk matrices are extensively applied in practice, there is currently a limited body of research with regards to guidance on their use (ibid). This thesis therefore aims to add to the currently limited guidance, considering suitability to its wide practical application for illustrating results of coarse risk analyses. The thesis investigated the risk matrix, its critique, and recommendations for improvement from the scientific community. Further, it studied how the risk matrix is designed and used in practice and to what extent the implementation of the recommendations from the scientific community would be suitable in the practical context of coarse risk analyses. This in order to bridge the gap between theory and practice, and provide recommendations from the scientific community, suitable to the practical application.

The recommendations from the scientific community were identified through a literature study in the form of a scoping review. From the scoping review, 15 unique recommendations for improving the risk matrix were identified.

To identify how the risk matrix is designed and used in practice, a documentation study was performed. The documentation was given from the project archive and client standards of ORS Consulting – a company performing a variety of coarse risk analyses where client risk matrices are oftentimes used. By looking at the design and implementation of risk matrices in various projects, it was possible to identify common characteristics of the matrices and their use. Furthermore, it was possible to make a first assessment of which recommendations may be practically suitable to apply.

To further identify which recommendations may be suitable in practice, interviews were performed. The interviews targeted people with experience of the risk matrix and using it as part of their profession. The interviews studied the opinions of the interviewees with regards to

the 15 recommendations provided by the scoping review and any practical limitations to implementing the recommendations.

With the help of the documentation study and interviews, six out of the 15 recommendations provided by the literature were deemed suitable in the context of coarse risk analyses. These are presented below:

- Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. View the tool with scepticism in mind.
- Make the risk matrix more comprehensible through a few simple visual improvements (e.g., increase cell size logarithmically if the scale is logarithmic)
- Provide guidelines on the use of risk matrix in case of an event with several categories of consequences (e.g., health, environment and financial consequences) and be clear on which consequence is mapped (worst case, most likely etc.)
- Clarify how risks that have the same score/position in the matrix should be prioritized.
- Establish the risk matrix with decision maker's risk appetite in mind.
- Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix.

The recommendations deemed to not be practically suitable shared the following common characteristics:

- Not practical due to time constraints.
- Made the matrix too complex and decreased user friendliness.
- Brought forward even more uncertainty.
- Was not beneficial as other easier means could be used for the same purpose.
- The recommendation could actually skew results in an undesirable way.

The majority of the identified suitable recommendations deal with increasing awareness of uses and misuses of the tool (e.g., clarifying how the tool should be used in case of different consequence categories or becoming aware of the tools limitation and that it should not be used on its own for decision making). This may indicate that the tool has been used without much thought and research. Potentially due to a lack of guidance, in line with Flage & Røed,'s research (2012). The recommendations also indicate that the simplicity of the risk matrix should not be compromised, in line with the notion of it being praised for this trait in the corporate world. It shall however be noted that excessive simplifications are part of the provided critique by Flage and Røed (2012).

Preservation of simplicity and time were factors deemed crucial when it came to visualizing results from coarse risk analyses in a risk matrix. It is important to note that the result may have been affected by the fact that the risk matrices and interviewees were identified in relation to coarse risk analyses. In other words, other recommendations from the litterature could have been deemed suitable to implement if the matrix was used to present results from another type of analysis.

Sammanfattning

En riskmatris är en tabell med rader som representerar konsekvenser och kolumner som representerar frekvenser. Riskmatriser kan användas som underlag för beslutsfattande kring acceptansen av en risk och prioritering av vilken risk som bör åtgärdas först (Duijm, 2015). Riskmatrisen anses också vara ett verktyg för att visualisera resultat från andra riskanalyser, så som exempelvis en Hazard Identification (HAZID) studie (Flage & Røed, 2012). Riskmatrisen har genom åren ökat i popularitet och hyllas särskilt för sin enkelhet i industrin (Cox, 2008). I dagsläget används verktyget flitigt när det gäller att presentera risk och föredras många gånger av ledningen på företag (Ale et.al, 2014). Ett användningsområde för riskmatrisen är rangordning och visualisering av scenarier som identifieras i grova riskanalyser (Baybutt, 2015). Kritik har dock framförts mot riskmatrisen. Bland annat gällande att den på egen hand inte anses utgöra en tillräckligt bra grund för beslutsfattande (Cox, 2008), att den förenklar något komplext (t.ex. representeras konsekvens med ett enda värde i stället för en fördelning av flera möjliga konsekvenser) (Flage & Røed, 2012) och att man går miste om den övergripande systemrisken då endast enskilda scenarier visualiseras (ibid). Vidare är användandet av riskmatriser påverkat av flera biaser (Duijm, 2015). Eftersom användandet är så utbrett inom industrin, samtidigt som verktyget ses som väldigt praktiskt, anses det orealistiskt att ersätta det med en annan metod (Flage & Røed, 2012).

Även om riskmatriser tillämpas i stor utsträckning, så är studier kring vägledning för dess användande begränsade (ibid). Detta examensarbete syftar därför till att komplettera den för närvarande begränsade vägledningen, med hänsyn till den praktiska lämpligheten i kontexten att illustrera resultat av grova riskanalyser. I inom ramen för examensarbetet undersöktes därför riskmatrisen, kritiken som framförts mot den och vilka rekommendationer för förbättring som presenterats av vetenskapen. Vidare studerades hur riskmatriser är utformade och används i praktiken, och i vilken utsträckning implementeringen av de rekommendationer som ges från vetenskapens håll är lämpliga inom den praktiska kontexten för grova riskanalyser. Detta för att överbrygga gapet mellan teori och praktik, och ge rekommendationer med teoretisk grund i vetenskap, som även anses praktiskt lämpliga.

Rekommendationerna identifierades genom en litteraturstudie i form av en scoping studie. Från denna erhölls 15 unika rekommendationer som syftar till att förbättra riskmatrisen.

För att identifiera hur riskmatrisen utformas och används i praktiken genomfördes en dokumentationsstudie. Dokumentationen hämtades från ORS Consultings projektarkiv och företagsstandarder. ORS är ett företag som utför en mängd olika grova riskanalyser, där kunders riskmatriser ofta används. Genom att titta på design och implementering av riskmatriser i olika projekt kunde återkommande egenskaper hos matriserna och deras användning identifieras. Vidare var det möjligt att göra en första bedömning av vilka rekommendationer från litteraturen som kan vara praktiskt implementerbara.

Intervjuer genomfördes för att vidare undersöka vilka rekommendationer som skulle kunna vara lämpliga i praktiken. Intervjuerna genomfördes med personer som har erfarenhet av riskmatriser och använder dessa som en del av sitt yrke. I intervjuerna dokumenterades och

studerades intervjupersonernas åsikter kring de 15 teoretiska rekommendationerna som givits i scoping studien. Detta för att identifiera eventuella praktiska begränsningar med implementeringen av rekommendationerna.

Med hjälp av dokumentationsstudien och intervjuerna ansågs sex av de 15 rekommendationerna från litteraturen vara lämpliga inom kontexten för grova riskanalyser. Dessa presenteras nedan:

- Gör de som tar fram riskmatriserna, riskbedömare och beslutsfattare medvetna om matrisens begränsningar och lyft fram svårigheter med verktyget. Var tydlig med att riskmatrisen kanske inte är det bästa verktyget för beslutsfattande, utan snarare en av många metoder som stödjer beslutsfattande. Se på verktyget med skepsis.
- Underlätta tolkningen av riskmatrisen genom enkla visuella knep (t.ex. öka cellstorleken logaritmiskt om skalan i matrisen är logaritmisk)
- Ge riktlinjer för användning av riskmatris för scenarier som har konsekvenser i flera olika kategorier (t.ex. konsekvenser för både säkerhet, miljö och ekonomi) och var tydlig med vilken konsekvens som kartläggs (värsta fall, mest troligt etc.)
- Förtydliga hur risker som bedöms likvärdiga/är i samma ruta i matrisen ska prioriteras.
- Etablera en riskmatris som har beslutsfattarnas riskacceptans i åtanke.
- Ha inte en stor variation av riskmatriser inom samma företag och område, om det inte finns olika riskaptit eller en tydlig motivering bakom den specifika riskmatrisen.

De rekommendationer som inte ansågs praktiskt lämpliga delade följande gemensamma egenskaper:

- Implementering av rekommendationen hade inneburit att analysen skulle ta mycket längre tid.
- Implementering av rekommendationen gjorde matrisen för komplex och minskade användarvänligheten.
- Implementering av rekommendationen ökade osäkerheten.
- Implementering av rekommendationen ansågs inte fördelaktigt då andra enklare medel kunde användas för samma ändamål.
- Rekommendationen kunde förvränga resultaten på ett oönskat sätt.

Majoriteten av de identifierade lämpliga rekommendationerna medför en ökad kunskap kring användandet av verktyget. Detta kan tyda på att verktyget har använts godtyckligt och utan vidare eftertanke. Möjligen på grund av dess enkla natur och den bristande vägledning som finns kring dess användande. Detta är således i linje med vad Flage & Røed, (2012) utrycker.

Bevarande av enkelhet och att inte göra proceduren tidsödande var faktorer som ansågs avgörande när det kommer till visualisering av resultat från grova riskanalyser. Det är viktigt att notera att resultatet kan ha påverkats av att riskmatriserna och intervjupersonerna identifierades i relation till grova riskanalyser. Andra teoretiska rekommendationer hade med andra ord kunnat bedömas vara lämpliga att implementera om matrisen använts för att presentera resultat från en annan typ av analys.

Table of Contents

1. Introduction

Being able to handle uncertainty and make decisions in an uncertain world is important both on an individual, corporate, and societal level. The uncertainty about the future is closely linked to what is often associated with the term "risk". As of now, there is not one universal definition of risk, however uncertainty is part of all definitions provided by the International Organization for Standardization (ISO) and Society for Risk Analysis (SRA) (Tehler, 2020). For instance, ISO 3100 defines risk as the following:

"The effect of uncertainty on objectives"

Further, risk may also be defined as a combination of a probability of an event and its consequences (ibid).

It was during the 20th century that the basis for modern risk management was initially developed, together with several ways of demonstrating risk. From the development of fault trees and event trees, FN curves and Probability Consequence Diagrams (PCDS), which have all now become part of the risk manager's toolbox (Ale et al., 2014). All of the previously mentioned ways of demonstrating risk gave way to the risk matrix (ibid). The risk matrix has gained more and more popularity within the corporate world through the years, and it has been extensively praised for its simplicity (Cox, 2008).

The risk matrix consists of a table where the columns represent consequences, and the rows represent frequencies/probabilities/likelihoods or vice versa. There are most often 3-5 levels of frequency/probability/likelihood and consequence. Each combination of a level for frequency/probability/likelihood and consequence yields a given position in the risk matrix. The matrix can be qualitative, semi-quantitative or quantitative (see Definitions). Oftentimes, each position in the matrix will be colour coded to represent a risk level or acceptance level (Flage & Røed, 2012). An example of a qualitative risk matrix is presented below in Figure 1.

Likelihood	Almost certain				
	Likely				
	Proabable				
	Unlikely				
	Highly Unlikely				
		Minor	Medium	High	Critical
		Consequence			

Figure 1 - Qualitative Risk Matrix Example

Risk matrices have two main applications according to Duijm (2015) - decision making about the acceptance of risk and prioritization of which risk should be addressed first. Moreover, the risk matrix can be considered by some as a risk analysis technique in itself (Flage & Røed, 2012). However, it can also be used to visualize results from other risk analyses. According to Flage & Røed (2012), the risk matrix should be considered a tool for visualizing the results from another risk analysis, and not a risk analysis technique in itself (ibid). One area of use when it comes to visualizing results, is with regards to risk ranking of hazardous scenarios identified in coarse risk analyses (Baybutt, 2015).

Risk matrices are oftentimes perceived as an understandable and convenient way of presenting risk. Many times, this is preferred by management and policy making bodies (Ale et.al, 2014). The use of risk matrices has been discussed by Cox (2008), with the conclusion that risk matrices do not support good decision making for risk management and that they should be used with caution. Flage and Røed (2012) agree with Cox, but state that as they are widely used, they do affect risk management in practice. Furthermore, many companies consider them useful (ibid). Therefore, simply replacing them with other tools might however be unrealistic (ibid). Instead, guidance should be provided (ibid).

Even though risk matrices are widely used in practice, there is currently a limited body of research with regards to guidance on their use (ibid). Only recently have publications occurred discussing the weaknesses of the risk matrix and potential recommendations for improvement of the tool (Duijm, 2015). With this in mind, there is a need for guidance on how the risk matrix should be used.

1.1 Purpose and Goals

This thesis aims to add to the currently limited guidance on the use of the risk matrix, considering suitability to its wide practical application for illustrating results of coarse risk analyses. Hence, the thesis will investigate the risk matrix, its critique, and recommendations for improvement from the scientific community. Further, it will also look at the practical application and limitations. This in order to bridge the gap between theory and practice, and provide recommendations from the scientific community, suitable to practical application.

The thesis will **study the scientific recommendations** with regards to improving the use of the risk matrix, then **investigate the "real life"** use of risk matrices in the context of coarse risk analyses and **assess to what extent the implementation of the recommendations are suitable in practice.**

1.2 Research Questions

In order to achieve the purpose and goals of the thesis, the scope is split into research questions to be answered. The following research questions apply:

1. *Which recommendations are provided for optimizing the use of the risk matrix in theory?*

2. *How is the risk matrix designed and used in practice in the context of coarse risk analyses?*

3. *How will the implementation of the theoretical recommendations work in practice and which ones are suitable to implement in the context of coarse risk analyses for various industries?*

1.3 Overview of Methodology

This chapter aims to present an overview of the methodology. The thesis is divided into three separate parts (given in Chapter 3,4 & 5 respectively) which aim to answer the research questions 1, 2 and 3.

The first part aims to answer research question number 1 through a scoping review of existing studies and in-depth analysis of relevant literature. This in order to find the recommendations provided for optimizing the use of the risk matrix in theory. The mindset of Arksey and O'Malley (2015) has been applied to this thesis. This means that the research question is kept broad in order to cater for any potential losses of relevant literature and hence recommendations. Therefore, research question 1 and subsequent scoping study was not limited to coarse risk analyses. The methodology and theory regarding scoping reviews as well as results from this part of the thesis are given in Chapter 3.

The second part of the thesis aims to answer research question number 2 through a review of actual documentation of coarse risk analyses where the risk matrix has been used. This

documentation is provided by the company ORS Consulting who perform coarse risk analyses for a wide array of clients. The intent is to study which risk matrices have been used, how they are designed and how the risk matrix has been applied as part of the risk analysis. Further, an analysis of the recommendations from the prior litterature study will be performed to identify which recommendations ***may*** be implementable based on what has been identified from the documentation. This in order to provide background for answering research question number 3. The methodology as well as results from this part of the thesis are given in Chapter 4.

The third and final part of the thesis aims to analyse whether the recommendations provided from the literature are applicable in practice and give an answer to research question number 3. This is done through interviews with a wide selection of persons who use the risk matrix as a part of their profession. Chapter 5 describes the interview methodology in detail. The final provided recommendations after the scoping review, documentation study and interviews are given in Chapter 6. The assessment of which theoretical recommendations are deemed suitable will hence be based on jointly studying the documentation and answers provided from interviews. Discussions regarding the results and methodology are provided in Chapter 7. Conclusions are given in Chapter 8.

1.4 Limitations

The following limitations apply:

- The risk matrices themselves will be studied with regards to improvement. Hence, an improvement of other types of analyses (e.g., HAZOP) with the help of the use of the risk matrix will not be covered.
- The risk matrices will be studied in the context of coarse risk analyses such as HAZOPs, HAZIDs, What-If's etc.
- The risk matrix will only be studied with regards to illustrating results. Hence, the use of the risk matrix as a risk analysis method on its own will not be covered.
- Any improvements with regards to *solely* better input values for the matrix will not be discussed as this is not considered an improvement of the tool itself. However, design of matrices (which might positively affect the input) will be covered, but no other ways of improving the input values (e.g., changing guidewords in a HAZOP).
- Alternative tools to use instead of the risk matrix (e.g., risk-networks or event trees) will not be discussed or proposed as improvements. However, continuous probability consequence diagrams (PCDS) are considered to be risk matrices.
- Recommendations for creating risk matrices within a completely new field will not be studied.
- The improvements will be based on, and provided by, current research given from a scoping review. Therefore, any personal improvement ideas from the writers or interviewees will not be presented as part of the results. They may however be part of a discussion.

2. Theory

As mentioned previously, a common tool for illustrating results from coarse risk analyses is the risk matrix. It is therefore important to know a bit about coarse risk analyses themselves. A risk analysis can be described as the following;

"The risk analysis shall identify the relevant initiating events and develop the causal and consequence picture. How this is done depends on which method is used and how the results are to be used. However, the intent is always the same: to describe risk." (Aven, 2015, p.2)

During a coarse risk analysis, hazardous scenarios are identified and their likelihood and consequences are assessed. For example, a hazardous scenario of fire in a building due to a short circuit in some electrical component can be deemed as likely with a medium consequence. This assessment of likelihood and consequence is then plotted into the risk matrix – i.e., results from a coarse risk analysis are presented with the use of the risk matrix.

A common coarse risk analysis is the Hazard and Operability (HAZOP) study. The result from the HAZOP may further guide which scenarios are subject to the next more in-depth analysis called Layers of Protection Analysis (LOPA). Additionally, the risk matrix may also be used to categorize scenarios identified in a Hazard Identification (HAZID) analysis. For both HAZOPs and HAZIDs, coarse assessments are made by experts in a workshop setting. The aforementioned risk analyses are presented in detail in Appendix A Chapter 10.1.

Risk acceptance is the basis for potential colouring of the risk matrix (Duijm, 2015) e.g., which scenarios identified in a HAZOP or HAZID are deemed acceptable or not. Frequently, the risk acceptance is illustrated in three levels: unacceptable (oftentimes coloured red), "broadly" acceptable (oftentimes coloured green) and scenarios where risk should be reduced ALARP (As Low As Reasonably Practicable) oftentimes coloured in yellow (ibid).

An example of an outcome of a risk analysis could be illustrated using the risk matrix as seen in Figure 2. In this case, two scenarios have been identified in a coarse risk analysis and mapped in the risk matrix.

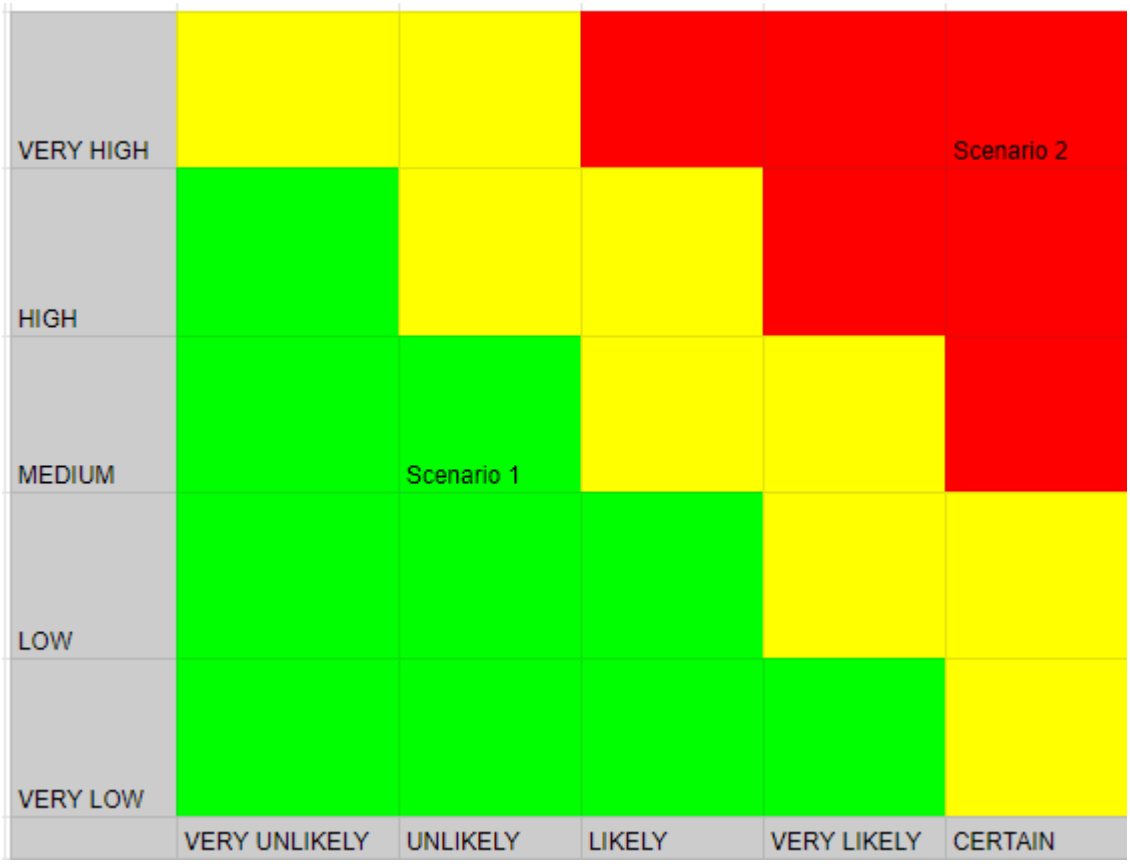

Figure 2 - Example of qualitative risk matrix with scenarios included.

In the case above, both the consequences and likelihoods are described purely qualitative. However, the case can also be that the likelihood is given as frequency intervals (e.g., very low = 10^{-7}-10^{-6}) whilst the consequences are still qualitative yielding a semi-quantitative risk matrix. In the case that the consequences are also given in numbers (e.g., Medium=cost of 10MUSD-100MUSD), the risk matrix will be purely qualitative.

The use of risk matrices has been criticized by for instance Cox (2008) and Flage and Røed (2012). First of all, Flage and Røed (2012) mention that one of the possible limitations of the tool is the application of a single value (or level) of consequences describing a hazardous scenario instead of a probability distribution of all possible consequences given a scenario. This means that the consequence mapped in a risk matrix is oftentimes the most commonly expected consequence. This is a coarse simplification, as there might be consequences that deviate substantially from the "typical" consequence. A recommendation given here is that the consequence mapping should be done prior to the likelihood mapping in risk analysis, so that the frequency matches the chosen consequence. For instance, consider the event A=stop of pump, where a pump stops 0,1 times per year and the typical consequence is asset damage of 100-200 USD. However, a potential consequence is also asset damage in such a way that it harms other surrounding equipment leading to a cost of 1000-2000 USD. But this frequency will then not be 0,1 times per year, but rather 0,0001 times per year. Therefore, it is important

to first assess the consequence and whether it is the most likely one, worst case or something else - and from thereon describe the frequency. It is hence important that it is clear which consequence is assessed in order to have a representative frequency.

Another major issue with the risk matrix is the assignment of risk acceptance levels (i.e., which coloured section the scenario represents) for individual scenarios whilst missing out on the full picture of the risk. As well as that, each scenario might be subdivided into more detailed scenarios (leak from pipe vs leak from small hole in pipe) pushing it towards lower frequency and hence yielding an accepted risk (Flage & Røed, 2012). There is also discussion with regards to the fact that the selected colour itself might affect the risk ranking, where "strong" colours such as red, yellow, and green tend to take the focus away from the scenario and on to mechanistic decision making (ibid).

The likelihood and consequence inputs for a risk matrix are oftentimes derived from subject matter experts and tend to be sensitive to biases (Hora, 2007). Biases with regards to the risk matrix have further been studied by Duijm (2015). Mainly, one bias is relevant - centring bias (i.e., people tend to choose values in the centre of an offered scale). It is mentioned that centring bias can be counteracted by extending the range of categories.

Duijm (2015) summarizes critique given by several authors, amongst others Cox (2008), Levine (2012) and Flage and Røed (2012). The following critique is addressed by Duijm (2015):

- Probability and consequences are in the case of risk matrix subjectively classified when it comes to assigning them to an identified event in a coarse risk analysis.
- There might be so-called "risk ties", where several scenarios are located in the same box of the risk matrix due to the poor resolution.
- There might be problems using standardized matrices for different fields – i.e., risk matrix must be relevant to its context.

More recommendations and critique exist in the scientific literature. However, recommendations provided in theory might not be suitable to real-life application of the tool.

3. Scoping Review

The scoping study methodology was chosen to answer research question number 1, as there was no need to focus on a very well-defined question and a broader topic covering many different study designs was of interest (Arksey & O'Malley, 2005). A scoping study makes it possible to get a broad overview of a topic whilst not being limited to a certain quality of study and study design when identifying relevant litterature (ibid). The aim of the thesis is to provide an overview of a field and give potential improvements, contrary to testing or developing a specific theory. Beerens and Tehler (2016) state that that the scoping study fits the purpose for this type of aim.

3.1 Scoping Study Methodology

The aim of a scoping study can be defined as the following:

"…to map the literature on a particular topic or research area and to provide an opportunity to identify key concepts; gaps in the research; and types and sources of evidence to inform practice, policymaking, and research" (Daudt et al., 2013, p.8)

Arksey and O'Malley (2005) provide a framework for conducting a scoping study. This framework has been further used in the scientific community by for instance Beerens & Tehler (2016). The framework consists of five steps to be undertaken for completing a scoping study. It should be noted that this is an iterative and non- linear process, hence redefinition of search terms and repeating of steps might be necessary (Arksey & O'Malley, 2005). Further, Levac, Colquhoun and O'Brien (2010) advance the framework provided by Arksey and O'Malley (2005). Therefore, the recommendations provided by Levac et.al (2010) have been used as part of the scoping study.

For further discussion regarding the methodology and its possible limitations, reference is made to Chapter 7.2

3.1.1 Step 1: Identify Research Question

The first step in Arksey and O'Malley's (2005) framework includes identifying a research question. This is done in order to guide the following search strategy (ibid). The recommendation given by Arksey and O'Malley (2015) is to keep the research question broad in order to cater for any potential losses of relevant literature. Also, Levac et.al (2010) give the recommendations to clearly articulate the research question and to consider the purpose of the scoping study when formulating the question. With this in mind, the research question chosen as part of the scoping study was:

What is known in the scientific literature about critique and guidelines for improvement with regards to risk matrices?

3.1.2 Step 2: Identify Relevant Studies

Different sources or databases might be needed to identify relevant litterature (Arksey & O'Malley, 2005). Beerens and Tehler (2016) differentiate between database selection (i.e., where the literature has been found) and search query identification (i.e., how the search has been performed).

The chosen database was Scopus. It is owned by Elsevier, EBSCO and Thomson Reuters and it covers a wide range of research fields, is multidisciplinary and the owners are various publishers (Beerens & Tehler, 2016). Further, this database is available for students through Lund University which makes it very practical to use. The aforementioned motivates the choice.

The search was done using a boolean search string in line with Beerens & Tehler's (2016) methodology. The search string included the keywords "Risk Matrix", "Guidelines", "Improvement", and "Critique" as these are crucial parts of the research question for the scoping study as well as the thesis. Since these keywords have synonyms, the keywords alone are not sufficient (Beerens & Tehler, 2016) to capture relevant literature (Arksey & O'Malley, 2015). For each keyword, a list of synonyms was therefore chosen. The keywords and synonyms as searched for in Scopus are given in Table 1. The use of "*" was chosen to identify different endings for the same word (e.g., improv* could give the words improve*ment*, improv*ing*, improv*e* etc.). Also " " was used around the keyword made up of two distinct words to symbolize that the exact two words should be searched for (i.e., "Risk Matrix" should be searched for, not "Risk" or "Matrix" on their own).

Table 1 Scoping study Keywords and Synonyms

	Synonym		
Keyword	"Risk Matri*"	"Risk Diagram"	-
	Guidelines	Framework	Standard
	Critique	Criticism	Review
	Improv*	Better*	Uplift

"OR" was used between the synonyms and "AND" was used between the Keywords, resulting in the following Boolean search string:

("Risk matri*" OR "Risk Diagram") AND (guidelines OR framework OR standard*) AND (critique OR criticism OR review) AND (improv* OR better* OR uplift).

The number of hits was noted after the search (1528).

Further, two inclusion criteria were applied:

1. The keyword Risk Matrix with its synonyms had to be a keyword in the literature.
2. Literature had to be in English.

Applying the above inclusion criteria led to the number of hits dropping to 98. Reference is made to Appendix B Chapter 10.2 with regards to motivation of the inclusion criteria 1 and 2, as well as a full list of inclusions and exclusion criteria as part of the further steps of the scoping study.

3.1.3 Step 3: Study Selection

In order to further select relevant studies, a method for excluding irrelevant literature had to be conducted. This can be done with the use of further inclusion and exclusion criteria (Arksey & O'Malley, 2005). To begin with, the initially identified 98 studies were subject to a title analysis as per Beerens and Tehler (2016). The title analysis was performed through additional inclusion and exclusion criteria. Papers that were clearly irrelevant based on the title were removed, whereas uncertain cases were kept for further analysis. This reduced the number of hits from 98 to 44.

Further, the abstracts of the 44 selected studies were reviewed. Levac et.al (2010) provide the recommendation that at least two reviewers shall independently perform the abstract review. Apart from that, reviewers are recommended to meet at the beginning, midpoint, and end stages of the abstract review to discuss potential challenges and uncertainties with regards to study selection (ibid). These recommendations were followed as part of the scoping study. Once the abstracts had been reviewed, 25 studies were kept for further analysis. This analysis of abstracts was done conservatively, hence the 25 studies included borderline cases.

3.1.4 Step 4: Charting the Data

Charting the data, as expressed by Arksey and O'Malley (2005), could be described as analysing the remaining studies for key items of information. This is done to sift through the studies to select those that answer the research question in the most detail. These shall then be further analysed to provide a basis for answering the research question (Arksey & O'Malley, 2005). Levac et.al (2010) recommend that the data extraction from the studies shall be done independently by the two reviewers and it should be considered an iterative process. These recommendations were followed.

To begin with, a read through of the entire material was performed. Three of the studies were behind a paywall and thus excluded from the read through (22 remaining). Some studies were then selected for deeper analysis depending on how they emphasize on criticism or suggestions for improvement regarding risk matrices. Studies selected for deeper analysis were labelled as Group 1, whereas remaining studies were labelled as Group 2.

Studies selected for deeper analysis needed to include suggestions on how the risk matrix can be improved or how it is critiqued in line with the research question presented in 3.1.1. Further, for the article to be covered in depth, it should not mainly cover manipulation of input data, improvement of other risk analysis tools such as HAZOPs (where the use of a risk matrix might

be a part of the improvement of the HAZOP). Also, the study was not chosen to be covered in depth if it mainly covered how information should be collected to improve the results of the matrix. These limitations are in line with the limitations of the thesis presented in Chapter 1.4. Further reference is made to Appendix C Chapter 10.3 with regards study titles, authors, years, summary of studies and motivations for group categorization.

Figure 3 showcases the overall process of the scoping review as a flowchart to be read top-down.

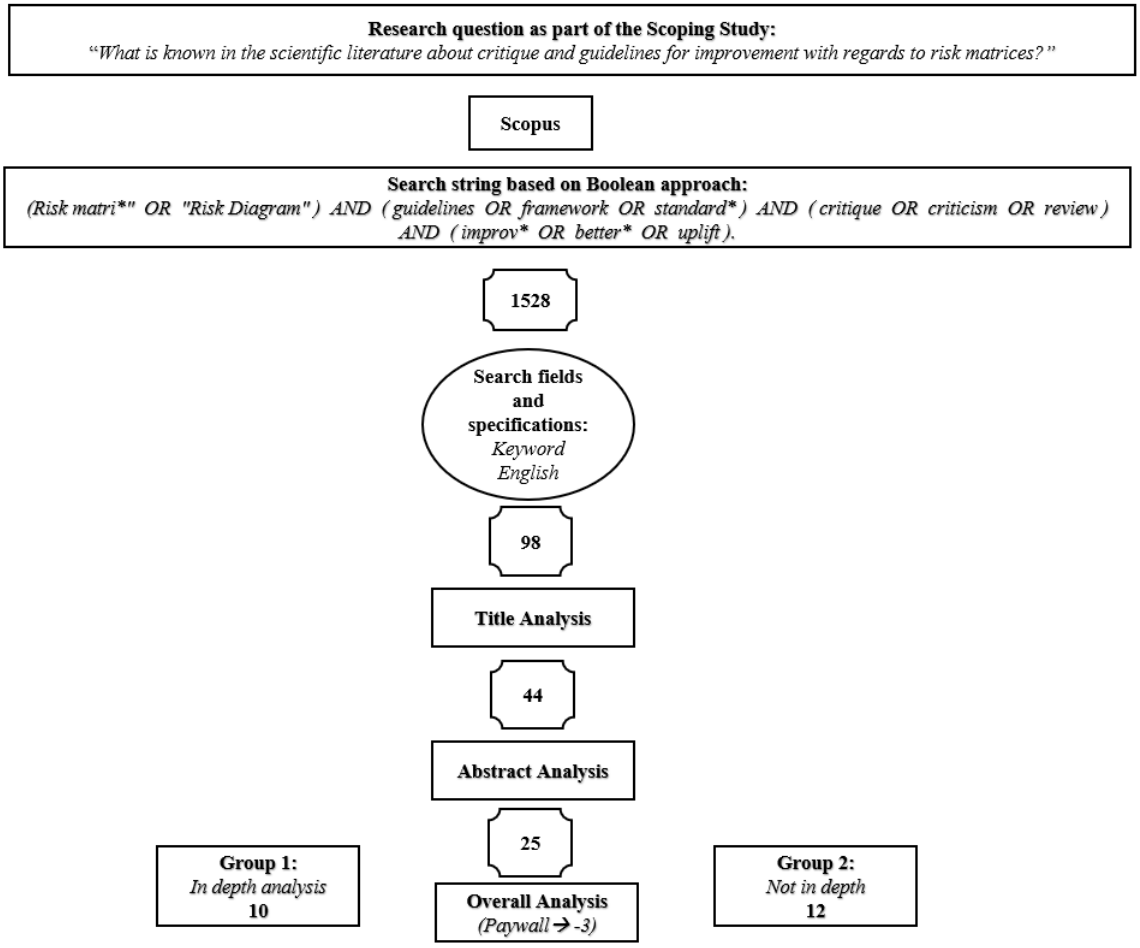

Figure 3 - Overview of the scoping study process

3.2 Step 5: Results from Scoping Review

3.2.1 Charting

During the scoping review, the information was charted meaning that it was sorted according to key points as described by Arksey and O'Malley (2005). This resulted in the fact that the 22 studies that were part of the overall analysis could be sorted into 9 categories. The categories and studies per category presented in Figure 4 below:

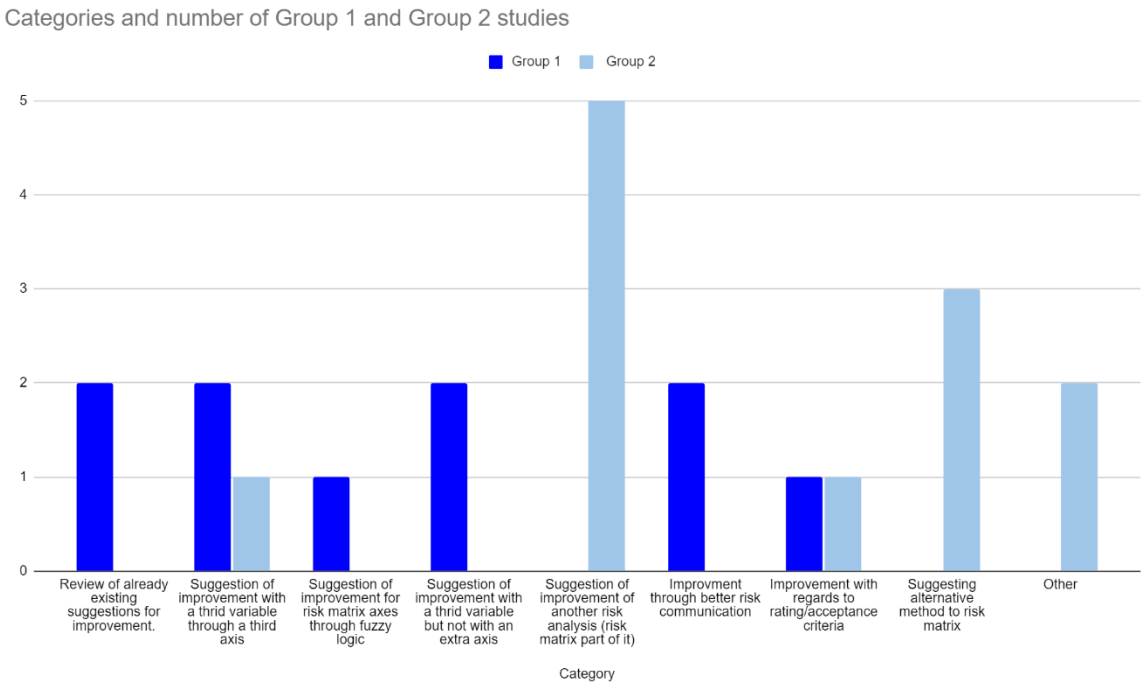

Figure 4 Categorization and number of Group 1 and Group 2 studies

Two studies included review of already existing recommendations and suggestions for improvement. Further, three studies suggest a similar improvement of the risk matrix - an addition of a third axis covering a third independent variable added to the current two-dimensional risk matrix. Improvement through fuzzy logic (i.e., converting linguistic terms into numbers) was mentioned in several studies. One of those covered using fuzzy-logic on the actual risk matrix axis, whereas the other studies mentioning fuzzy-logic did so in relation to the input of the risk matrix (e.g., as part of the HAZOP). With regards to improving the risk matrix through a third independent variable, apart from using a third axis, two studies suggested visualizing an added variable in the current 2D risk matrix (e.g., through intervals).

Five studies covered the improvement of a risk analysis where the risk matrix is part of the overall analysis but not the focus (e.g., improving the HAZOP with the use of a risk matrix).

Two studies proposed improvement of the risk matrix through communication. In this case the improvement was with regards to how the risk matrix can become more comprehensible based on experimental studies of how people understand e.g., logarithmic axis. Further communication improvements include or suggestions to simply view the risk matrix as a tool to create greater risk awareness (subsequently viewing the risk matrix with scepticism).

Two studies covered the improvement of the risk matrix through better definition of acceptance criteria (e.g., establishing the risk matrix with decision maker risk attitudes in mind). Furthermore, three studies did not suggest improvement of the risk matrix itself, but rather stated that another type of tool should be used under certain conditions. Finally, two studies did not fit into any of the above categories. One of those did not discuss the risk matrix as a tool itself and no critique/improvements were given. The study discusses risk assessments in general but not risk matrices in particular (i.e., mentioned a variety of risk assessment tools where risk matrix is one of them). The other study did not give any improvement suggestions and only described limitations of the risk matrix.

3.2.2 In-Depth Analysis

The following chapter describes the outcome of the in-depth analysis of group 1 studies identified in the scoping review. The studies were analysed for results and outcome that refer to the research question as recommended by Levac et.al (2010).

The research question for the scoping study was to identify what is known in the scientific literature about critique and guidelines for improvement with regards to risk matrices. The answer to this question based on the in-depth analysis is given in this chapter. The in-depth analysis will further be used to answer research question number 1 for the thesis - i.e., which recommendations are provided for optimizing the use of the risk matrix in theory. The link between the in-depth analysis and the thesis research question 1 is given in Chapter 3.3 in the form of recommendations provided from the in-depth studied literature.

Several studies reference critique to Cox (2008), Duijm (2015), Flage and Røed (2012) and Levine (2012) which is presented under Chapter 1 and 2. Therefore, only unique critique/recommendations identified within the studies of group 1 is presented below.

The article written by Gulsum, Ward, and Clarkson (2019) highlights the use of risk matrices in healthcare in England, where the main problem identified is a lack of guidelines for how risk matrices should be used and consideration of the inherent limitations of the risk matrix. Further, it is noted that a large variety of risk matrices are used at different hospitals, which one might think is due to different risk appetites. However, this study did not find an explanation for the use of the various risk matrices. Instead, it was noted that risk was prioritized differently depending on which matrix was used, which is incorrect. Therefore, it should be noted that a large variety of risk matrices may not always be positive if there is no thought behind why a specific matrix is used. Clarkson et.al (2019) provide several recommendations for improving the use of the risk matrix. The recommendations are summarized as the following:

- When using the risk matrix, other factors than only likelihood and consequence should be considered. This can be e.g., strength of knowledge. To illustrate this, Clarkson et.al (2019) suggest a third dimension to the matrix.
- Provide guidelines on the use of risk matrix in case of an event with several categories of consequences (e.g., if there are consequences to both health, environmental and financial)
- Clarify how risks that have the same score/position in the matrix should be prioritized.

- Be clear on the fact that the risk matrix is not a tool for decision making, but rather one of many methods supporting decision making. In other words, the risk matrix shall not be the only basis for decision making.

Li, Yee, Tan, Lee (2014) study how risk matrices are used in supply chain risk assessment. They express the opinion that risk matrices do not reflect the true complexity of risks in supply chains. If the risks of a company's supply chain are not assessed properly, it becomes difficult to assess which are the most critical and make correct decisions with regards to mitigation measures. They express that a weakness of the risk matrix is that it does not visualize the complexity of risks, this is however not just a problem that affects only supply chain risk management, but several different areas have risks that are complex due to the design of the system itself. Lee et.al (2014) also suggest improvement to the risk matrix through the use of a third (and in their case even fourth) dimension. For Supply Chain Risk Management (SCRM) these axis/dimensions are said to be detectability and recoverability. Further, through their case study, Lee et.al (2014) demonstrate that with the use of these dimensions, risks are ranked differently than they would in a 2-D risk matrix. Moreover, risks with low probability but high impact are considered more significant with this improvement to the matrix, as they also have low detectability. It is worth noting that even though Lee et al. (2014) provide improvements to a risk matrix used in SCRM, they point out that their work can be applied to other industries as well. Hence, the improvement through more dimensions could be considered as per Clarkson et.al (2019) and Lee et.al (2014). This dimension might be detectability, recoverability, strength of knowledge or potentially something else.

Vatanpour, Hrudey and Dinu (2015) reference the critique provided by Cox (2008), namely the issue with the risk matrix with regards to making error through assigning higher rankings than necessary to lower risks. Specifically for cases when the severity and likelihood are negatively correlated and where Cox (2008) states that the assessment using risk matrices might be “worse than random”. The study by Dinu et.al (2015), further demonstrated this issue identified by Cox (2018), through a practical experiment where the theoretical concern was validated. Furthermore, Dinu et.al (2015) also mention other limitations of the risk matrix as per ISO 31000:

- A matrix should be designed in such a way that it is appropriate for the circumstances. This means that it may be difficult to standardize and apply a common system across a range of circumstances.
- To define scales might be difficult with regards to unambiguity.
- Different individuals might rate a risk differently, i.e., the use of the risk matrix can be subjective.
- Aggregation is not possible (i.e., one cannot assess whether 5 “Low” risk scenarios are identical to one “Medium” risk scenario)
- Risks with different categories of consequences are difficult to compare or combine.

The suggestions for improvements that Dinu et al. (2015) present are characterized more by a qualitative approach, where one gets to take risk matrices for what they are. The limitations must be acknowledged and therefore the risk matrix is to be regarded as information to guide the decision maker more than prescribing the decision itself. Further, the risk matrix can be viewed as a tool for promoting discussions about risk priorities in an organization. The matrix

is to be viewed with a healthy amount of scepticism and with its limitations in mind. Furthermore, the fact that one needs to be clear regarding the fact that the risk matrix is only one of many methods for supporting decision making and not a basis for the decision itself, is in line with the previous recommendation given by Clarkson et.al (2019).

Aven (2017) lifts previous critique with regards to the risk matrix. Specifically, Aven (2017) focuses on the critique that risk cannot be captured by using only two dimensions - probability and consequence. Focus is on the knowledge aspect which has not been given enough attention. The concept of strength of knowledge with regards to improvement of the risk matrix is hence what is further explored in the study. Aven (2017) is of the opinion that two dimensional matrices should not be used, but instead a third axis with strength of knowledge should be introduced. This in combination with prediction intervals as a means of having a more fluid measure of consequence - i.e., capturing a spectrum of consequences. With these measures the risk matrix should be a better reflection of reality and lead to a better visualization of the present risks. Hence, a third and potentially fourth dimension suggested by Aven (2017) is in line with what has been previously suggested by Clarkson et.al (2019) and Lee et.al (2014).

Freeman, Dryhuerst, Recchia and Sutherland (2021) provide an experimental study with regards to perception, use and increased comprehension of risk matrices. Based on previous studies, suggesting that logarithmic scales may be helpful, and even better if they are geometrically labelled with more "familiar" numbers (e.g., having labels/categories 1, 5, 25 showcasing that each one is five times more likely than the other) as well as visualizing the non-linearity by increased cell shape. Freeman et.al (2021) conduct experiments testing these hypotheses. Further, Freeman et.al (2010) mention that using legends might require more cognitive demand as the working memory has to keep either the legend or the diagram active whilst looking at the other. However, having a too cluttered risk matrix may also decrease cognitive performance (ibid). The results of the experiments indicate that there may be changes to the traditional risk matrix design that can improve the comprehension of the risk matrix. These are presented below:

- Using non-linear scale labelling for matrices with exponential or otherwise non-linear increase (i.e., having likelihood categories labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the categories labelled as 1,2,3,4).
- Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each category increases)
- Integrating information directly into the risk matrix instead of using legends (under the assumption that the risk matrix will not become too cluttered).

The results of these recommendations are presented in Figure 5 below:

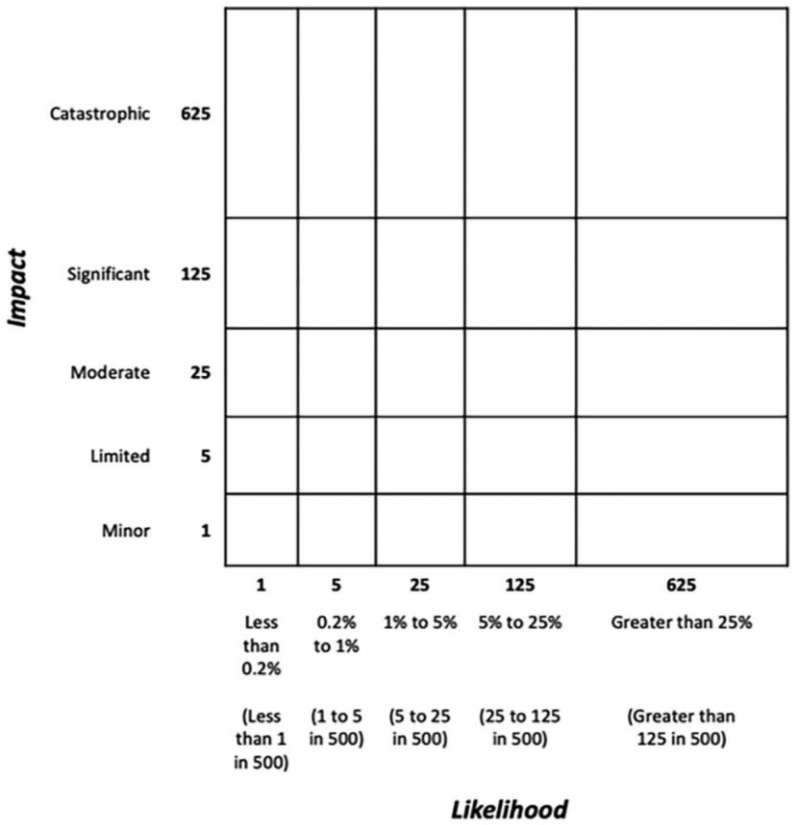

Figure 5- Suggested improvements to the risk matrix (Freeman et.al, p.17, figure 8)

Goerlandt and Reniers (2015) provide a thorough review with regards to representation of uncertainty in the PCDS (where the risk matrix is a type of PCDS). To begin with, it is mentioned that uncertainty has not been given enough attention and that there have been limited proposals on how to visualize this key feature of risk in the risk matrix. Further, it is essential to understand that uncertainty can be due to natural variation (i.e., aleatory/outcome uncertainty) or due to lack of knowledge (i.e., epistemic/evidence uncertainty). Goerlandt and Reniers (2015) first explore the current proposals on how to visualize the different dimensions of uncertainty. Further, a new way of visualizing is presented as per Figure 6.

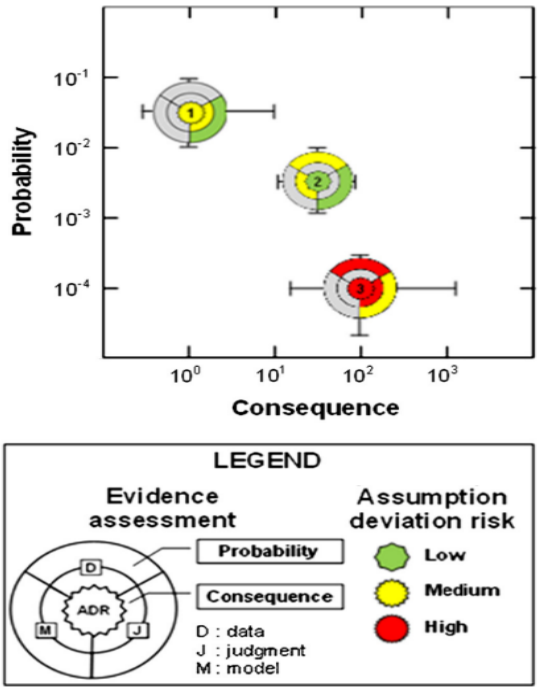

Figure 6- Proposed model by Goerlandt and Reniers (2015)

The proposed model showcases natural variation through prediction intervals (i.e., lines in the graph) and the epistemic/evidence uncertainty through bubbles. The probability and consequence evidence uncertainty is divided, and assessed for the dimensions of the input data, model, and judgment. The evidence uncertainty is further showcased through colour where the uncertainty can be low, medium, or high. This improvement to the risk matrix is in line with the suggestions provided by Aven (2017) with regards to including strength of knowledge in the risk matrix (i.e., how certain one is about the knowledge behind the values). In this case, it is not suggested to include the strength of knowledge through a third axis, but instead through visualizing this third dimension in a 2-D graph.

Duijm (2015) explores weaknesses with the risk matrix as described by previous studies and ISO, and provides recommendations for use and design of the risk matrix. These are further discussed in Chapter 2. Duijm (2015) takes the position that assigning discrete categories of probability and consequence (i.e., through "gridding" the risk matrix), is not the best way of capturing uncertainty. This is because assigning a scenario in a cell is a statement that the scenario will not exceed neither the upper nor the lower limit. This can be problematic if the grid is not large enough or the scenario is located close to one end of the grid. Hence, Duijm (2015) suggests an improvement of the risk matrix by having fluid continuous consequence scales and that uncertainty should be visualized with independent cells of different sizes. It should be noted that Duijm (2015) points out that this improvement does not solve some inherent issues with the risk matrix such as subjective assignment of probability and frequency, aggregation, use of corporate risk matrices and consequence ambiguity (i.e., if the defined consequence should be the worst possible or most likely etc.). The suggested improvement to the risk matrix is presented in Figure 7.

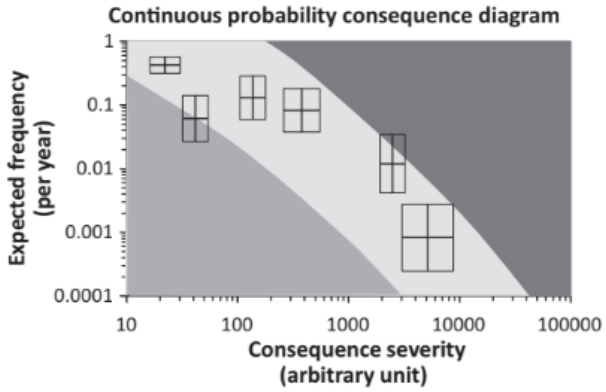

Figure 7- Proposed risk matrix by Duijm (2015)

Ruan, Yin and Frangopol (2015) mention that risk attitudes of decision makers are not always integrated as a part of the risk matrix. One way to integrate the risk attitudes is through utility theory and utility functions. The specific approach to incorporate risk attitudes through utility curves will not be discussed further as part of this thesis. However, Frangopol et.al (2015) mention that it is extremely important to establish a risk matrix that considers the risk attitudes of the decision makers as this will enhance the practicability and rationality of the risk matrix. This approach will allow risk visualization/assessment to be in line with actual opinions of the decision makers. Hopefully, this will help diminish inefficient and irrational decisions (ibid). The aim is to bridge the gap between assessor and decision maker where the matrix should reflect how the decision maker perceives risk and their attitude to risk.

Pascarella, Rossi, Montella, Capasso, De Feo, Botti Snr, Nardone, Montuori, Triassi and D'Auria (2021) summarize critique and suggestions for improvement by Cox (2018), Duijm (2018), Ruan et al. (2015), Aven (2017) and others described above. It does paint a picture of the science-sphere's different approaches to improvements of the risk matrix and the large variety of improvement suggestions. Capasso et al. (2021) agrees with the fact that risk matrices generate ambiguity in results, and that they are so widespread and commonly used it is difficult to migrate to a different method. Therefore Capasso et al. (2021) is of the opinion that it is more productive to make designer's risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. In other words, the study suggests an improvement that is simply to become aware of the provided critique and limitations presented in various studies. This is in line with Dinu et.al (2015).

Risk matrices have different formats, and this makes it difficult to compare matrices according to Hong, Pasman, Quddus and Mannan (2019). This is a problem that particularly arises when the axis in the matrix is qualitative and has a linguistic scale. For example, it is mentioned that it is difficult to compare or merge different results from different matrices in a company/ at a plant, as people tend to interpret words differently. Therefore, the authors have proposed a method to transform the scales on the axis from linguistic terms to numbers through type-2 fuzzy logic. This should lead to all matrices getting uniform axis and to a greater opportunity for eliminating the subjectivity in the grading of the axis that linguistic terms entail.

3.2.3 Citation and Reference Analysis

Even though the scoping review aimed to get a broad overview of the topic and answer the research question, the search was still limited with regards to the database Scopus and the search string used. In order to capture any key literature that might have been missed, a citation analysis and a reference analysis was performed.

The citation analysis was performed using VOSviewer, where Scopus data was directly extracted and analysed based on whether the studies cite each other. The results are given in Figure 8 (all 22 studies analysed - Group 1 and Group 2) and Figure 10 (10 in-depth studies analysed - Group 1 only). The size of the nodes indicates how many times the study has been cited overall, whereas the connections indicate that the two studies have cited each other. The colour of the nodes illustrates which year the study was published.

Figure 8- Results from citation analysis of Group 1 and Group 2 studies

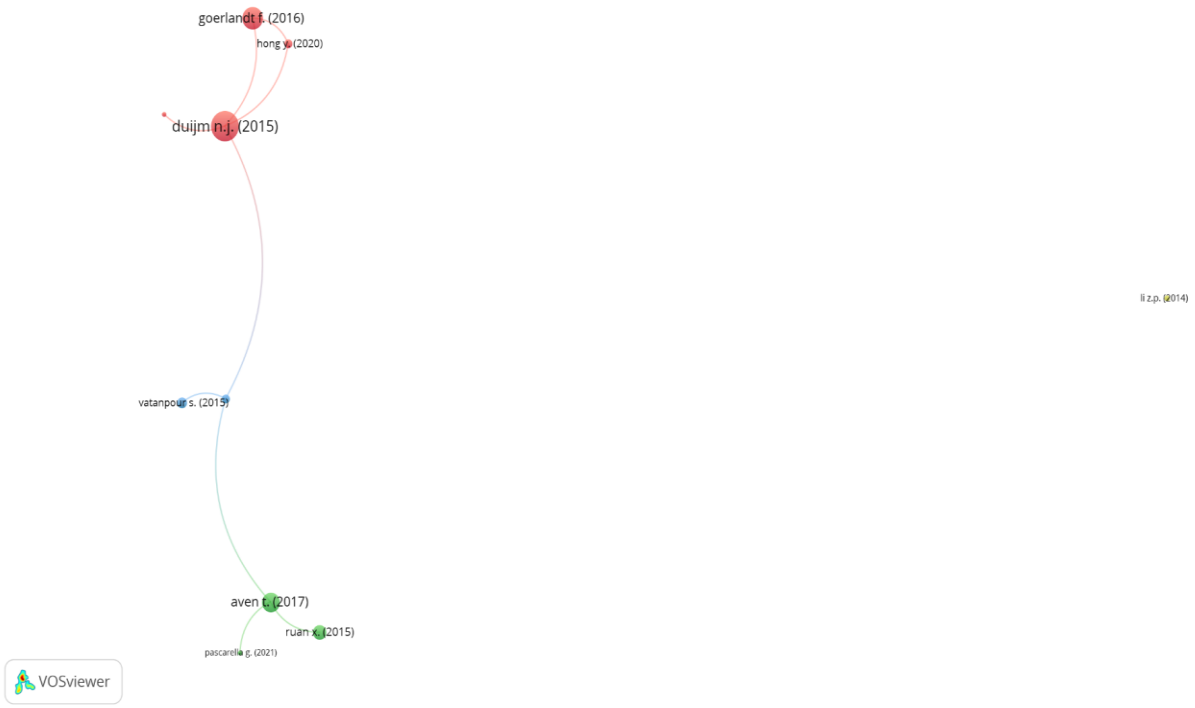

Figure 9- Results from citation analysis of Group 1 studies

The results indicate that for the combination of Group 1 and Group 2, there are several studies that have not been cited by each other. However, looking at the Group 1 studies only, all but one study has made citations to each other within Group 1. This might indicate that the provided ideas from the in-depth analysis might be limited as they all stem from each other or build upon each other's thoughts. However, the case might also be that the sorting into Group 1 & 2 might have been done well, as most outliers in Figure 8 might simply be articles covering less relevant topics.

Furthermore, there was an indication that some articles not covered by Scopus were actually the base for the litterature identified in the scoping study. To check whether this was the case, Cox (2008) was identified as a reference and it was noted how many of the 22 articles reference Cox (2008). 14 out of 22 articles referenced Cox (2008), and this might further indicate that all critique has not been captured as the majority of given critique is initially provided by Cox (2008).

As the citation analysis mainly showcases relationships between articles, it was also important to capture any key *missed* articles that might be relevant but had not been captured due to the choice of database and/or search string. This was done through a review of references of all Group 1 & 2 studies (1159 references in total). Occurring references with relevant titles were identified by systematically going through the reference pages. This methodology was chosen due to the fact that identified studies referencing other unidentified studies (but with a relevant title) may indicate that there was literature that had not been captured by the scoping review even though it is still relevant for the topic. 18 titles from the reference analysis were considered relevant. Reference is made to Appendix D Chapter 10.4 for details regarding the identified relevant studies. Two of the relevant studies identified in the reference analysis yielded a recommendation each. Reference is made to recommendation 15 and 3 in Table 2.

3.3 Outcome of Scoping Study - Theoretical Recommendations

Table 2 contains 15 recommendations given from the litterature study. It hence provides an answer to research question 1 derived from the scoping study and reference analysis. Further, the recommendations are divided into categories. For a further motivation of the given recommendations from litterature, reference is made to Appendix H Chapter 10.8.

Table 2- Summary of recommendations from in-depth analysis.

No	Recommendation	Reference
Recommendations for establishing a completely new matrix		
1	Establish the risk matrix with decision maker's risk appetite in mind (e.g., through a utility function).	Ruan, Yin and Frangopol (2015)
2	Consider having a continuous probability-consequence diagram instead of gridding the matrix as this will improve e.g., resolution. Reference is made to Figure *7*.	Duijm (2015)
3	If the risk matrix is to be used for prioritization of risks, consider using the Sequential Updating Approach (SUA) for defining the rating schemes (number of ratings/colours used in the matrix and how to assign these to different cells).	Bao, Li & Wu (2018)
Expand/add to risk matrix		
4	Consider the complexity of risks by adding a third or fourth dimension to the risk matrix (e.g., detectability, recoverability, strength of knowledge). Other factors than likelihood and consequence should be considered.	Li, Yee, Tan, Lee (2014) & Aven (2017) & Gulsum, Ward, and Clarkson (2019)
5	Visualize uncertainty in a 2D matrix through e.g., adding prediction intervals or boxes together with colour schemes for epistemic uncertainty specifically. Further split the epistemic uncertainty into categories (data, model etc). Reference is made to Figure 6 and Figure 7	Goerlandt and Reniers (2015), Flage and Røed (2012), Aven (2017) & Duijm (2015)
Visual improvements for increased comprehension of the tool		
6	Make the risk matrix more comprehensible through a few simple visual improvements provided in Figure *5* - Use non-linear scale labelling for matrices with exponential or otherwise non-linear increase (i.e.,	Freeman, Dryhuerst, Recchia and Sutherland (2021)

No	Recommendation	Reference
	having likelihood categories labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the categories labelled as 1,2,3,4). - Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each category increases). Consider a logarithmic formatting of cells. - Integrate information directly into the risk matrix instead of using legends (under the assumption that the risk matrix will not become too cluttered).	
7	Counter centring bias by extending the range of categories.	Duijm (2015)
Improve the use of the risk matrix		
8	Provide guidelines on the use of the risk matrix in case of an event with several categories of consequences (e.g., consequences for both health, environment and financial).	Gulsum, Ward, and Clarkson (2019)
9	Clarify how risks that have the same score/position in the matrix should be prioritized.	Gulsum, Ward, and Clarkson (2019)
10	Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. Acknowledge the following limitations of the risk matrix and view the tool with scepticism in mind: - A matrix should be designed in such a way that it is appropriate for the circumstances. This means that it may be difficult to standardize and apply a common system across a range of circumstances. - To define scales might be difficult with regards to unambiguity. - Different individuals might rate a risk differently in a coarse review such as e.g., HAZOP where consequence and likelihood is assigned to an event, i.e., the use of the risk matrix can be subjective. - Aggregation is not possible (i.e., one cannot assess whether 5 “Low” risk scenarios are identical to one	Dinu et.al (2015) , Duijm (2015), Clarkson et.al (2019) , Flage and Røed (2012)and Capasso et.al (2021)

No	Recommendation	Reference
	"Medium" risk scenario) - Application of a single value (or category) of consequences describing a hazardous scenario is made instead of a probability distribution of all possible consequences given a scenario – i.e., simplifications are made. - Risks with different categories of consequences are difficult to compare to one another or combine.	
11	Consequence mapping should be done prior to likelihood mapping in risk analysis when using risk matrices and clarify which consequence is assessed (e.g., "typical" or worst case).	Flage and Røed (2012)
12	Be aware of the fact that assignment of risk acceptance levels (i.e., which coloured section the scenario represents) for individual scenarios cannot determine the full picture of the risk picture (i.e., it is not possible to aggregate scenarios or determine risk on system level using risk matrices).	Duijm (2015)
13	Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix.	Gulsum, Ward, and Clarkson (2019)
Modify existing risk matrix		
14	Consider transforming qualitative axes of the risk matrix to quantitative grading e.g., through fuzzy logic.	Hong, Pasman, Quddus, Mannan (2019)
15	If the risk matrix is used within a process hazard analysis (PHA), calibrate the risk matrix with regards to risk acceptance, where the individual or group risk criteria is divided by the estimated number of hazardous scenarios leading to the same hazard.	Baybutt (2015)

4. Documentation Study

This part of the thesis aims to answer research question 2 of the thesis - i.e., how the risk matrix is designed and used in practice in the context of coarse risk analyses. Further, an analysis of the recommendations from the prior litterature study will be performed to identify which recommendations ***may*** be suitable to implement. This in order to provide background for answering research question number 3.

4.1 Documentation Study Methodology

In order to obtain data regarding how risk matrices are designed and used in practice in coarse risk analyses, the project archive and client standards from ORS Consulting were studied. Further, personnel at ORS were contacted for their input for additional matrices to study that were not identified through archive or client standards. A step-by-step methodology is presented in Figure 10.

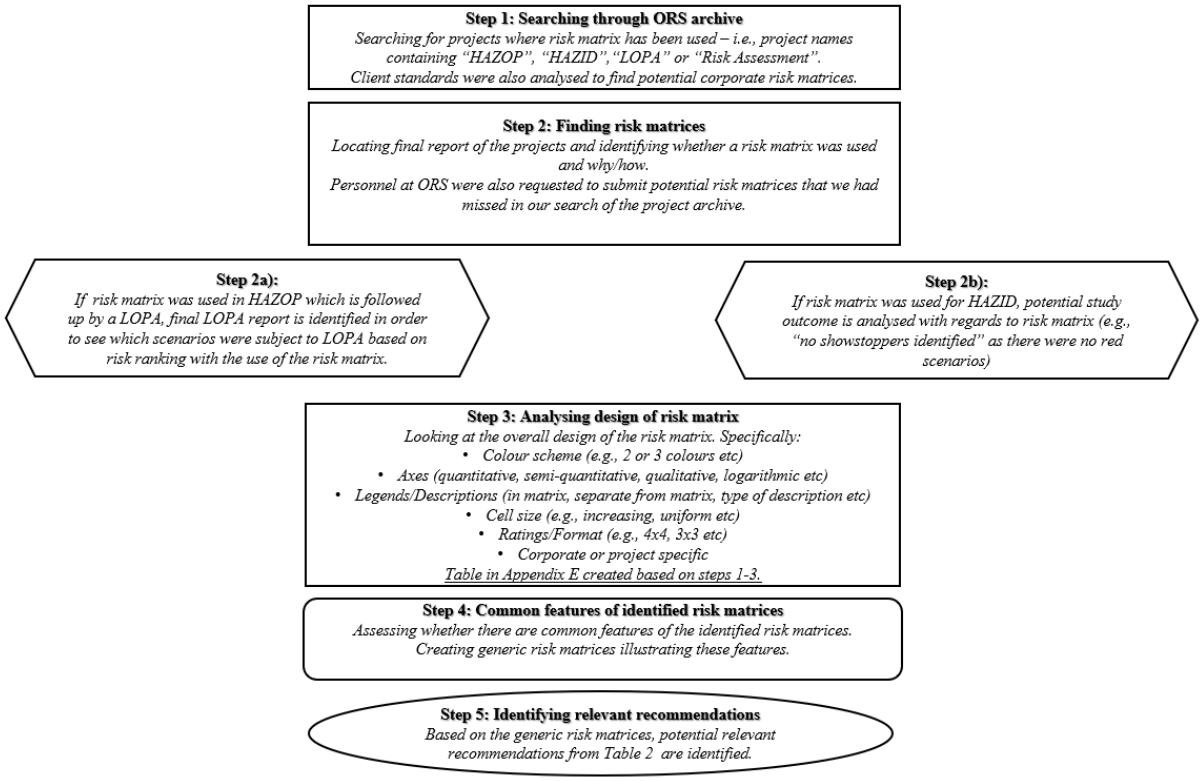

Figure 10- Step-by-step methodology for the assessment of data regarding practical implementation of risk matrix

This methodology was chosen as it provided the possibility to answer research question 2. Step 1 and 2 identified risk matrices. ORS was chosen due to their extensive experience in using risk matrices as part of coarse risk analyses as well as their broad client base. Step 2a and 2b identified how the risk matrix was used in coarse risk analyses. Step 3 provided an insight with regards to the risk matrix design. Step 4 was performed due to confidentiality as it was not possible to reveal the actual risk matrices identified. The identified matrices were instead used to highlight common features, from which new risk matrices were created to reflect common features of the confidential matrices identified. For further discussion regarding the methodology and its possible limitations, reference is made to Chapter 7.3

It shall be noted that the analysis in Step 5 could not cover all aspects of the potential improvements of the risk matrix. For instance, it was not possible to assess whether there was a centring bias or whether risk acceptance was based on decision maker's attitudes.

4.2 ORS Consulting

ORS Consulting (ORS) was established in 2009 as an independent and specialist provider in the field of risk management advisory services. During the 14 years in service, ORS has worked with over 100 different clients and over 1000 projects with the same goal - to prevent losses and increase safety. ORS has offices in Sweden, Norway, Scotland, and Denmark - but clients all over the world.

4.3 Creation of Generic Risk Matrices Based on Common Characteristics

Representative risk matrices capturing main common features were created based on the risk matrices identified - i.e., Step 4 of the documentation study methodology. The representative risk matrices are presented in Figures 11-14 under Chapter 4.3.1-4.3.4.

The matrices identified were given a unique number and described based on information gathered in steps 2a), 2b) and 3. The matrices originate from a total of 18 ORS reports and 2 matrices were provided without reference to a report. Further, each identified matrix was categorized into types 1-4 respectively. A total of 16 unique matrices were identified. See Appendix E Chapter 10.5 for further details of each identified risk matrix.

4.3.1 Matrix Type 1 – Matrix with consequence categories

Matrix type 1 consists of a legend free 5x5 or 6x5 matrix (5x5 illustrated in Figure 11) with uniform cell sizes with three to four colours (illustrated as three in Figure 11). The consequences and frequencies are divided into linear levels with names "A-E", "1-5" or "P0/C0-P5/C5". Each level is further described in the matrix qualitatively (e.g., A=very unlikely for frequency, or A=Catastrophic for consequences). In some matrices, the levels for frequency are further described quantitatively by logarithmic intervals of 10 (e.g., A=Very unlikely=0,00001-0,0001). The consequences are most often divided into categories of Reputation, Environment, Asset and Safety, where Reputation and Environment consequences are described qualitatively, whereas Asset and Safety are described either qualitatively only or quantitatively (e.g., large property damage or >100 MUSD and Several fatalities or 3-10 fatalities). Matrix Type 1 was the most common type of matrix identified (6 out of 16 matrices was of this type). Furthermore, it was used in different types of industries and was part of several different risk analyses - most commonly HAZOP and LOPA.

Consequences						Frequency				
						Level 1 (e.g., 1 or A or P0 etc)	Level 2	Level 3	Level 4	Level 5
						Qualitative description 1 - e.g., very unlikely	Qualitative description 2	Qualitative description 3	Qualitative description 4	Qualitative description 5
Reputation	Environment	Asset	Safety			Potentially quantitive description 1 e.g., 0,00001-0,0001	Potentially quantitive description 2	Potentially quantitive description 3	Potentially quantitive description 4	Potentially quantitive description 5
Qualitative description 1	Qualitative description 1	Qualitative quantitative description 1 E.g., large property damage or <1000 MUSD	Qualitative or quantitative description 1 E.g., 3-10 fatalities or several fatalities	Qualitative description 1 -e.g., Catastrophic	Level 1(e.g., A or 1 or S0 etc)					
Qualitative description 2	Qualitative description 2	Qualitative or quantitative description 2	Qualitative or quantitative description 2	Qualitative description 2	Level 2					
Qualitative description 3	Qualitative description 3	Qualitative or quantitative description 3	Qualitative or quantitative description 3	Qualitative description 3	Level 3					
Qualitative description 4	Qualitative description 4	Qualitative or quantitative description 4	Qualitative or quantitative description 4	Qualitative description 4	Level 4					
Qualitative description 5	Qualitative description 5	Qualitative or quantitative description 5	Qualitative or quantitative description 5	Qualitative description 5	Level 5					

Figure 11 Generic risk matrix type 1

4.3.2 Matrix Type 2 – Matrix with legend

The matrix type 2 is a matrix in the format of 5x5, 5x4 or 6x5 with 3-6 colours, uniform cell size and an attached legend. The axes are graded with letters or numbers for consequence and frequency levels. The explanation of each number and letter for consequence and frequency is described in detail in an attached legend to the matrix. The legend can include several different consequence categories such as asset, environment, reputation etc, which are expressed either qualitatively or quantitatively. The matrix has been used for HAZID to draw conclusions regarding an overall design, as well as scenario ranking in HAZOP where scenarios with a certain risk ranking were further subject to LOPA.

Figure 12 Generic risk matrix type 2

4.3.3 Matrix Type 3 – Matrix without consequence categories

Matrix type 3 consists of a legend free 5x5 or 6x5 matrix (5x5 illustrated in Figure 13) with uniform cell sizes and three colours (red, yellow, green). The consequences and frequencies are **not** divided into levels with their own labelling. Instead, frequencies are described qualitatively as well as quantitatively directly on the axis with logarithmic intervals of 10. Further, consequences are described purely qualitatively but no legend is provided for further understanding of the qualitative descriptions. Consequences are also not classified into environment, reputation, safety etc. This risk matrix is presumed to be the most "basic" and was only found in 2 out of the 16 risk matrices analysed. Furthermore, the matrix was used in HAZID and HAZOP studies to rank scenarios, however it was discarded for the HAZID as it was identified to be too unclear and subjective. For the HAZOP, the project identified using this matrix is ongoing, hence it was unclear whether scenarios based on HAZOP risk ranking with risk matrix would be further used in LOPA.

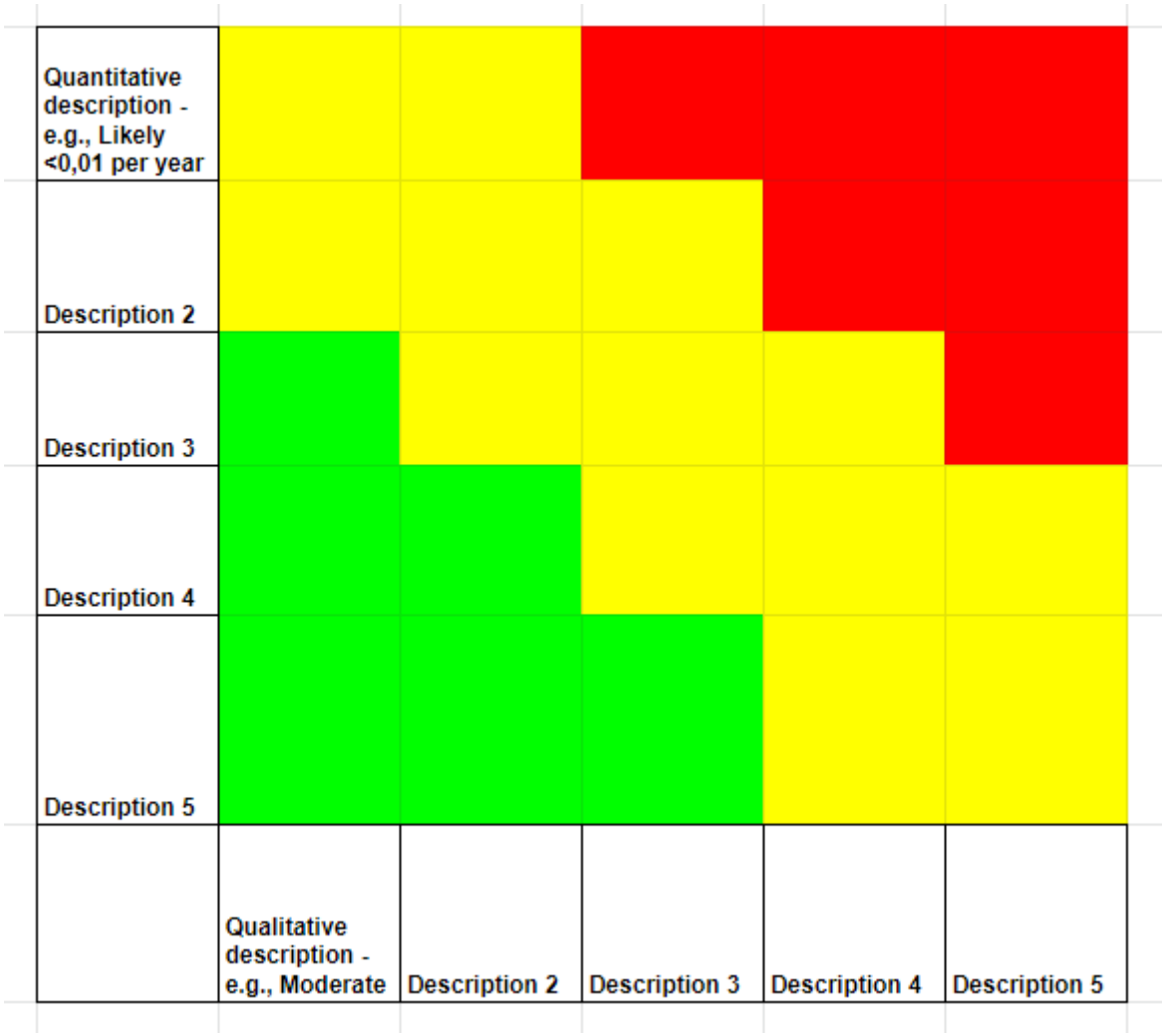

Figure 13- Generic risk matrix type 3

4.3.4 Matrix Type 4 – Matrix with frequency and consequence categories

Matrix type 4 consists of a legend free 6x6 matrix with uniform cell sizes and four risk rating colours. The consequences and frequencies are divided into linear levels with names such as “F0-F4”, and “C0-C4”. The consequences are most often divided into categories of Reputation, Environment, Asset and Safety where all levels and categories are described qualitatively. Each frequency level is divided into three classes based on the use of the risk matrix. In case of risk matrix being used for HAZID, frequency should be described qualitatively. In other cases, it is given quantitatively in intervals. Matrix Type 4 was the most uncommon type of matrix identified. Risk matrix used for risk ranking scenarios in HAZOP. Scenarios rated “yellow” were further taken to LOPA.

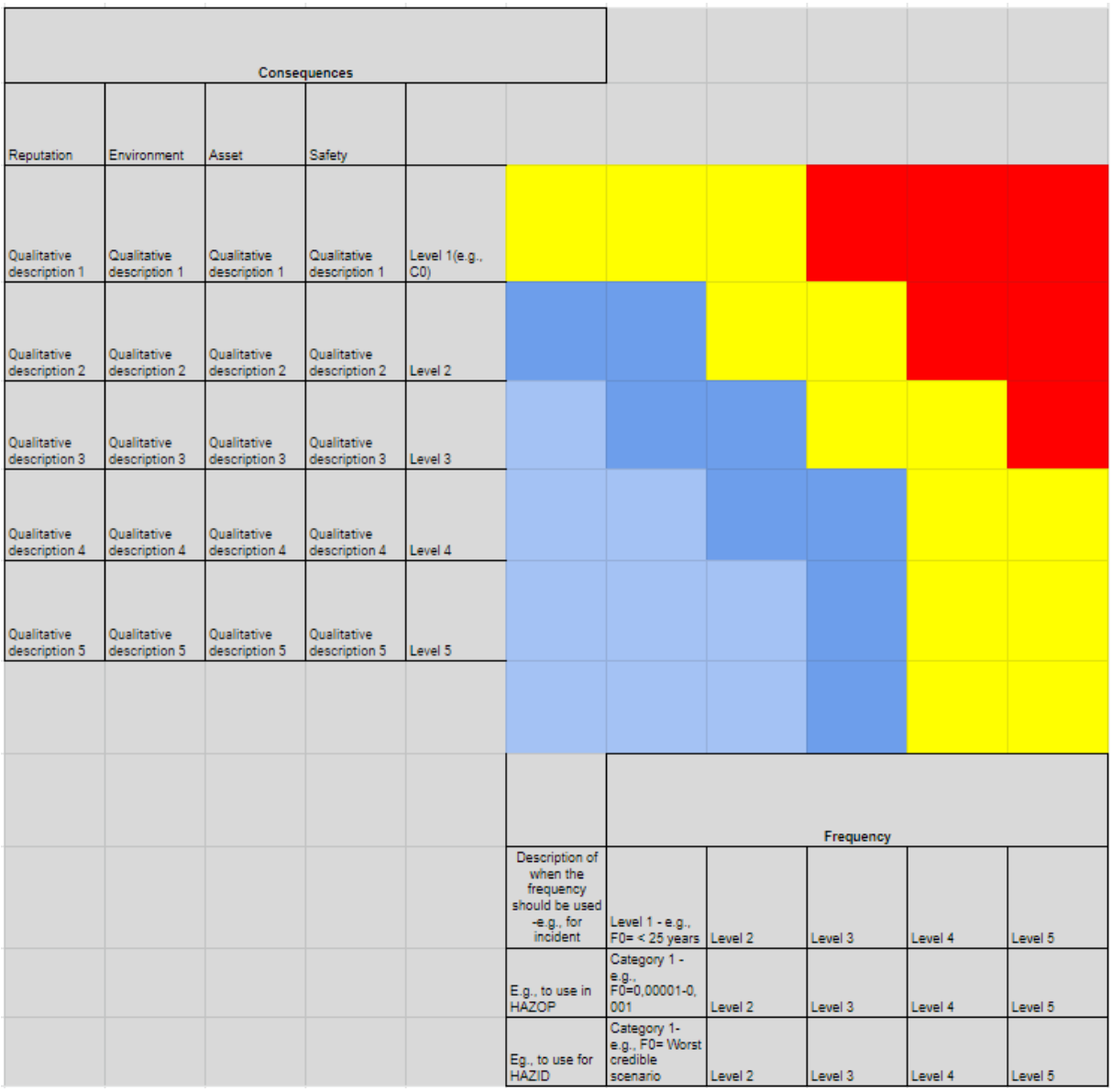

Figure 14 Generic risk matrix type 4

4.4 Conclusions Based on Documentation Study

Table 3 contains an initial assessment of which recommendations from the litterature study that might be practically applicable considering the use and design of risk matrices in coarse risk analyses.

Table 3- Identified relevant recommendations and motivation.

No	Recommendation	Conclusions based on documentation study
Recommendations for establishing a completely new matrix		
1	Establish the risk matrix with decision maker's risk appetite in mind (e.g., through a utility function).	It is not possible to assess from the documentation whether acceptance criteria have been based on decision makers or something else (e.g., best industry practice).
2	Consider having a continuous probability-consequence diagram instead of gridding the matrix as this will improve e.g., resolution. Reference is made to Figure 7.	What has been seen in practice, is that the assessment of scenarios from e.g., HAZOPs and HAZIDs are done based on the colour scheme of a specific cell. It is not possible to assess from documentation whether it would create additional value to identify exact values for probability and consequence using a continuous PCDS.
3	If the risk matrix is to be used for prioritization of risks, consider using the Sequential Updating Approach (SUA) for defining the rating schemes (number of ratings/colours used in the matrix and how to assign these to different cells).	This approach might create more grids and colours in the matrix. Based on practical applications of risk matrices, the colours are used for assessment. Having more colours might create value but might also simply mean that "both yellow and orange" go to LOPA from a HAZOP.
Expand/add to risk matrix		
4	Consider the complexity of risks by adding a third or fourth dimension to the risk matrix (e.g., detectability, recoverability, strength of knowledge). Other factors than likelihood and consequence should be considered.	Based on the data obtained regarding how the risk matrix is designed and used in practice, this recommendation might be practically applicable. All identified matrices are 2-dimensional looking at frequency and consequence only, hence relevant for matrix types 1-4.

No	Recommendation	Conclusions based on documentation study
5	Visualize uncertainty in a 2D matrix through e.g., adding prediction intervals or boxes together with colour schemes for epistemic uncertainty specifically. Further split the epistemic uncertainty into categories (data, model etc). Reference is made to Figure 6 and Figure 7.	Based on the data obtained regarding how the risk matrix is designed and used in practice, this recommendation might partially be applicable. Regarding visualization through prediction intervals, the practical application of risk matrices shows that the uncertainty is built into the interval length or width of the category. However, visualizing uncertainty regarding strength of knowledge (epistemic) similar to Figure 6 can be practically applicable if a third axis is not preferred as this is currently not the case for the obtained risk matrices. Relevant for matrix types 1-4.
Visual improvements for increased comprehension of the tool		
6	Make the risk matrix more comprehensible through a few simple visual improvements provided in Figure 5 - Use non-linear scale labelling for matrices with exponential or otherwise non-linear increase (i.e., having likelihood categories labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the categories labelled as 1,2,3,4). - Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each category increases). Consider a logarithmic formatting of cells.	Based on the data obtained regarding how the risk matrix is designed, this recommendation can be practically applicable. No identified matrices have these types of visual tricks to improve perception, hence relevant for matrix types 1-4.

No	Recommendation	Conclusions based on documentation study
	- Integrate information directly into the risk matrix instead of using legends (under the assumption that the risk matrix will not become too cluttered).	
7	Counter centring bias by extending the range of categories.	Based on the data obtained regarding how the risk matrix is designed, this recommendation can be practically applicable. Based on identified matrices it is not possible to assess whether the categories are large enough or their range is wide enough to counter centring bias.
Improve the use of the risk matrix		
8	Provide guidelines on the use of the risk matrix in case of an event with several categories of consequences (e.g., consequences for both health, environment and financial).	Based on identified matrices it is not possible to assess whether guidelines are provided for how to handle an event with several consequence classes. Hence this recommendation might be applicable if guidelines have not been provided for matrix types 1-4. From projects identified where risk matrices have been used, the risks are ranked based on every class in the matrix as part of the HAZOP. Scenarios are then split and assessed individually in the LOPA - e.g., scenario 1s, 1a, 1e is the same scenario but 1s is the scenario with consequences for safety, 1a is the scenario with consequences for assets etc. 1a, 1s, 1e are hence further individually subject to LOPA.
9	Clarify how risks that have the same score/position in the matrix should be prioritized.	Based on identified matrices and use of them, this recommendation may not be relevant or applicable. This is because when risks are ranked, they are ranked based on colour and not risk score/cell. Therefore, it may not be of value to e.g., clarify how two scenarios with the same

No	Recommendation	Conclusions based on documentation study
		score in a yellow cell are distinguished since they would both be taken from HAZOP to LOPA in practice or valued equally in a HAZID.
10	Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. Acknowledge the following limitations of the risk matrix and view the tool with scepticism in mind: - A matrix should be designed in such a way that it is appropriate for the circumstances. This means that it may be difficult to standardize and apply a common system across a range of circumstances. - To define scales might be difficult with regards to unambiguity. - Different individuals might rate a risk differently, i.e., the use of the risk matrix can be subjective. - Aggregation is not possible (i.e., one cannot assess whether 5 "Low" risk scenarios are identical to one "Medium" risk scenario) - Application of a single value (or category) of consequences describing a hazardous scenario is made instead of a probability distribution of all possible consequences given a scenario – i.e., simplifications are made.	Based on identified matrices it is unclear whether designers, risk assessors and decision makers are aware of the limitations of the matrix and know the difficulties with the tool. This recommendation may hence be applicable to all matrix types. There are indications that the limitations may not be known in practice, as data obtained points to the fact that decisions are made and conclusions are drawn based on the risk matrix ranking in a HAZID only (e.g., "no showstoppers in the design" based on no red scenarios). Further, scenarios are selected for further investigation and assessed for need of added safeguarding (i.e., decided to be important or not important to assess) based on the risk matrix only as e.g., yellow scenarios are most often subject to LOPA whilst green ones are discarded. However, this might simply be a way of sorting out the most important scenarios and not actually directly making decisions.

No	Recommendation	Conclusions based on documentation study
	- Risks with different categories of consequences are difficult to compare to one another or combine.	
11	Consequence mapping should be done prior to likelihood mapping in risk analysis when using risk matrices and clarify which consequence is assessed (e.g., “typical” or worst case).	Based on identified matrices and use of them, it is not possible to assess whether the consequences or frequencies are mapped first, and which consequences are assessed. Hence, this recommendation may either not be relevant (already implemented) or still relevant.
12	Be aware of the fact that assignment of risk acceptance levels (i.e., which coloured section the scenario represents) for individual scenarios cannot determine the full picture of the risk picture (i.e., it is not possible to aggregate scenarios or determine risk on system level using risk matrices).	Based on identified matrices and use of them, this recommendation can be applicable and relevant for all risk matrix types. This due to data obtained pointing to the fact that sometimes conclusions are drawn based on the risk matrix ranking in a HAZID or HAZOP only (e.g., “no showstoppers in the design” based on no red scenarios). In other words, a conclusion regarding the whole system or design is made based on the assessment that no individual scenarios are within unacceptable levels.
13	Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix.	Based on identified matrices and use of them, this recommendation might not be very relevant or practicably applicable. Most matrices have been corporate. It is not possible to assess whether there have been clear motivations of differentiation.

No	Recommendation	Conclusions based on documentation study
Modify existing risk matrix		
14	Consider transforming qualitative axis of the risk matrix to quantitative grading e.g., through fuzzy logic.	Based on identified matrices and use of them, this recommendation might be applicable to matrix type 1-4 as they all have purely qualitative elements. However, the approach fuzzy logic might be too advanced to practically implement as it requires obtaining data regarding what different linguistic terms mean for a variety of personnel.
15	If the risk matrix is used within a process hazard analysis (PHA), calibrate the risk matrix with regards to risk acceptance, where the individual or group risk criteria is divided by the estimated number of hazardous scenarios leading to the same hazard.	Based on identified matrices and use of them, this recommendation might be applicable as many risk matrices identified were used in PHAs and were corporate - i.e., not calibrated for the specific project or risk analysis.

5. Interviews

The interviews performed as part of this thesis, aim to further analyse whether the recommendations from the litterature presented in Chapter 3.3 and further analysed in Chapter 4.4, are applicable in practice and suitable to implement in the context of coarse risk analyses. This will give an answer to research question number 3. The methodology and its motivation is presented in Chapter 5.1.

5.1 Interview Methodology

The reason for choosing to conduct interviews instead of e.g., questionnaires was the fact that the interviews aim to identify opinions, which can be difficult using questionnaires according to Höst, Regnell and Runesson (2006).

According to Brinkman and Kvale (2014), there are no standardized procedures for conducting a scientific interview. However, there are standard choices when it comes to techniques (ibid). Some of these have been implemented and are described below. The dialogue between the interviewer and interviewee sparks personal contact and new insights into the world of the interviewee. In this context, the interviewee is presumed to have expertise necessary in order to investigate the suitability of the identified recommendations.

The interviews were performed as qualitative, semi-structured, interviews. The reason for having a qualitative interview instead of a quantitative (completely structured) one, is due to the fact that there is emphasis on the interviewee's point of view, their interpretation, and opinions (Bryman, 2018). In this case regarding practical suitability of the suggestions for improvement of the tool. A semi-structured form of the interview, as opposed to a completely unstructured one, was used as specific themes needed to be covered, and mainly in the correct order (ibid) - i.e., all identified recommendations needed to be covered.

Bryman (2018) points out that if there is a clear focus (i.e., are the recommendations suitable) instead of a general wish to "explore" a certain topic (e.g., how people feel about risk matrices) - a semi-structured interview is preferred. Furthermore, Bryman (2018) mentions that if there are several cases that need to be compared to one another, such as the different recommendations, a certain structure is necessary, which the semi-structured interview provides. Additionally, the semi-structured interview also favours flexibility and potential to ask follow-up questions (ibid), which is appreciated as it provides further insights into opinions of the interviewees.

In the preparations for the interview, Kvale and Brinkmann (2014) stipulate that the following should be clarified:

- Why - the purpose of the study.
- What - acquire knowledge on the subject.
- How - to acquire knowledge of theories and techniques for interviewing and analysis of the results of the interview.

The purpose of the interview study was already specified as research question number 3 for the thesis. Furthermore, knowledge about the subject was acquired through the previous literature study and document study in Chapters 3 and 4. The theory and technique for the interviews was acquired through studies of literature on the subject of research interviews, to provide a basis for choosing the type of interview and how it should be set up and performed. Furthermore, the mindset of the interviewers is very important, and it should be noted that openness for unexpected results is crucial (Gerson and Damaske, 2020).

Before conducting a semi-structured interview, an interview guide should be prepared in order to verify that the planned themes are covered (Bryman, 2018). This guide can be more or less structured (ranging from a simple memory list to specific questions). The main point is however, that the questions asked makes it possible for the interviewer to get information about the interviewee's point of view and that the interview guide is conducted in such a way that there is room for flexibility (Bryman, 2018).

The questions regarding what *needs* to be known after the interview can also be used to create the interview guide – i.e., whether a specific recommendation given from the litterature is deemed suitable in practice (ibid).

Bryman (2018) proposes some recommendations to be considered when preparing for an interview and creating an interview guide:

- Create order in such a way that questions follow a reasonable timeline. However, be prepared to potentially change the order of the questions.
- Create questions in such a way that it facilitates answering the overall research question.
- Use a language that is reasonable considering the background of the interview person.
- Note down background information about the person being interviewed (e.g., position in organization, age, name etc.).
- Do not ask leading questions.
- Become familiar with the environment in which the interviewee is working. This will facilitate the interpretation of answers given.
- Record and transcribe the interview as it is otherwise easy to miss specific phrasing and expressions.
- Make sure the interview is conducted in a calm area (no background noise) where the interviewee knows that what is said will not be heard by anyone else.

Recording was performed in Microsoft Teams as part of the interviews. Bryman (2018) mentions several times that recording is an essential part of qualitative interviews. This is because the interviewer is interested both in *what* is said as well as *how* it is said (ibid). In order to capture these features, a full exposition of the interview needs to be available (ibid). By recording both sound and picture, all features of the interview are captured. Furthermore, the need for writing extensively whilst conducting the interview is removed which further removes distraction from the interview. This is important as a semi-structured interview requires full focus on what is being said, since answers are analysed continuously to ensure that the scope is covered fully (Gibson & Brown, 2009). Finally, as the interviews were conducted with two interviewers at the same time, potential missing of the scope was diminished as the other party

could lead the interview in the correct direction if they noticed that the scope was not being covered properly. Notes were taken throughout by the person not interviewing (so that the interviewer could have full focus on the interview) and important timestamps were noted down so that potentially extra relevant parts could be transcribed.

According to Brinkmann and Kvale (2014), the first few minutes of an interview are crucial as it is when the interviewee forms an opinion about the interviewer before they allow themselves to speak freely and express themselves about opinions on a topic. It is important that the interviewer creates a good contact with the interviewee by showing interest, understanding and respect for what the interviewee shares and is clear about what the interviewer wants to know through the interview (ibid).

With the following in mind, the interview guide conducted is presented in Table 4. As illustrated, by following this guide - all recommendations from Chapter 3.3 are assured to be covered.

Table 4- Interview guide

#	Question/Subject	Recommendation covered
1	Overall introduction - introducing us, creating context and explaining purpose. Be clear on the fact that it is okay to say "I do not know. This is too detailed"	N/A
2	Introduction of interviewee - Provision of background information about the person being interviewed and the environment in which the interviewee is working.	N/A
3	Are you aware of any limitations with regards to using the risk matrix? *(e.g., aggregation is not possible, not only tool for decision making, difficulty with standardization)*	10 & 12
4	What is your opinion on adding a third or fourth dimension to the risk matrix (e.g., detectability, recoverability, strength of knowledge) apart from consequence and probability? What could that dimension be? Show examples to the interviewee. Are there any limitations to doing this?	4
5	What is your opinion on the integration of prediction intervals for uncertainty? Are there any limitations to doing this?	5
6	What is your opinion on showcasing epistemic uncertainty in the risk matrix? How would you do that? Show an example to the interviewee. Are there any limitations to doing this?	5

#	Question/Subject	Recommendation covered
7	There are some studies with regards to plain visual improvements of the risk matrix for increasing perception. What is your opinion with regards to changing category labels, increasing cell sizes and removing legends? Are there any limitations to doing this?	6
8	Would you consider extending the risk matrix axis to decrease centring bias? Are there any limitations to doing this?	7
9	Are guidelines provided on the use of risk matrix in case of an event with several classes of consequences (e.g., safety, financial and reputation). Would you consider providing guidelines and are there any limitations to doing it?	8
10	How are risks with the same score/in the same cell prioritized? Are there any guidelines for prioritization? Would you consider providing guidelines and are there any limitations to doing that?	9
11	When using the risk matrix, which mapping is done first, and which consequences are usually assessed? *(i.e., do you look at consequences or frequencies first, is the most likely or worst-case consequence)*	11
12	Have you used various risk matrices or only one corporate one? What is your experience with using many different risk matrices? What is the motivation behind the differentiation?	13
13	Do you think it would be practicable and valuable to change qualitative labels to quantitative? *(e.g., through fuzzy logic)*	14
14	If you use the risk matrix in a PHA, is the matrix calibrated with regards to expected number of scenarios leading to the same hazard? Do you think it would be practicable and valuable to calibrate the risk matrix? *(i.e., the individual or group risk criteria is divided by the estimated number of hazardous scenarios leading to the same hazard)*	15
16	Have you ever been a part of creating a new risk matrix? How was it designed, which values were assigned?	1 & 2 & 3
17	What is your relation to the risk matrix? *(e.g., potential critique, how the person uses it, like/dislike, other aspects of improvements). Question is provided to capture any missed results from earlier.*	N/A

Selection of interviewees was based on availability and role. As ORS Consulting was part of the thesis, four interviewees with relevant expertise were chosen from ORS. Furthermore, in order to broaden the view, the majority of participants for the interviews were chosen from outside of ORS. These participants were identified partly on the advice of ORS, who provided contact information and performed an initial screening for other relevant companies and authorities. Using the network of ORS to identify other participants (when they are themselves part of the study) can be referred to as snowball sampling (Guest, Namey & Mitchell, 2013). Additionally, relevant stakeholders were identified independently and contacted by phone.

As it was considered more important to select the right kind of participants (i.e., those with the correct contextual knowledge about risk matrices and those using them often as part of illustrating results from coarse risk analyses), rather than many participants, the snowball methodology was chosen (Gerson & Damaske, 2020). Kvale and Brinkman (2014) mention that the number of interviewees is usually between 15 +- 10 which was fulfilled. Furthermore, as the role of the participants differ substantially, several perspectives were provided which is beneficial according to Guest et.al (2013). The interviewees are given in Table 5.

Table 5- Interviewee List

Name	**Position**	**Company**
Esteban Bernechea Rojas	Principal Consultant	ORS
Carl Bonde	Seveso supervisor	MSB
Richard Forss	Global Process Safety Manager	Perstorp
Johan Ingvarson	Researcher	Lund University - LTH
Anders Jakobsson	Company Owner	AJ Risk Engineering
Thomas Lackman	Section Manager and Consultant at Safety	AFRY
Mathias Nevrell	Production Manager	Voestalpine Precision Strip AB
Morten Nilstad Pettersen	Country Manager	ORS
Thomas Solberg Fylking	Principal Consultant	ORS
Carsten Stegelmann	Country Manager	ORS

5.2 Interview execution

The interviews began with a presentation of the interviewer, the thesis and context as well as purpose with the interview (Brinkmann & Kvale, 2014). After that, any questions the interviewee had were addressed in accordance with recommendations from Brinkmann and Kvale (2014).

The interviewee was then requested to present themselves, and specifically covering the points given by Bryman (2018). This presentation also gave the possibility for the interviewer to create good contact with the interviewee (Brinkmann & Kvale, 2014). This further facilitates an environment where the interviewee feels comfortable sharing opinions.

In order to increase the provided answers and help the memory of the interviewee when questions are asked about past experiences, a few recommendations provided by Brinkmann and Kvale (2014) were implemented. These were:

- Giving the interviewee time to think and verifying that it is normal to not be able to answer quickly.
- Trying to give specific timestamps such as "when was the last time you….".

Follow-up questions were not provided in a standardized way, but instead given based on the context and based on full focus on the interview and answers provided (Brinkman & Kvale, 2014).

After the interview, some points were noted in accordance with the recommendations provided by Bryman (2018) in order to evaluate how the interview was conducted. These were the following:

- How the interviews went (the state of the interviewee e.g., nervousness, collaboration).
- Where the interview was conducted.
- Other experience of the interview
- Environment (calm environment, background noise etc).

The outcome from the interviews with regards to these points is given in Appendix G Chapter 10.7.

After the first interview, to improve the interview methodology further, the HR/education responsible at ORS (Gitte Nählinder) was contacted for input. Information regarding how to approach different personality types was provided. Further a recommendation was given to show questions (one at a time) and examples of matrices in a Google Slides presentation during the interview. This yields easier understanding of the question and provides a complete visual aspect for the interviewee. Therefore, a presentation used in all following interviews was created.

5.3 Analysis of Interviews

An analysis of the interviews should be conducted as part of the interview methodology (Brinkman & Kvale, 2014). It should consider the purpose of the study and identify themes (ibid). After each interview, results were summarized and discussed between the interviewers. A comparison of answers provided by the interviewees was performed after conducting all interviews. Finally, overall themes were identified. Reference is made to Appendix F Chapter 10.6 for a detailed summary of each interview.

The study purpose was to identify which recommendations may be suitable to implement in the context of coarse risk analyses. The interviews served to identify the opinions of the interviewees with regards to the identified recommendations from the litterature. Themes identified in the interviews were the following:

- Recommendations met with generally positive attitudes.
- Recommendations met with generally negative attitudes.
- Recommendations met with highly miscellaneous attitudes.

Generally, positive attitudes were expressed with regards to simple visual improvements for increased comprehension of the matrix (recommendation no 6) and addition of guidelines for using the risk matrix in case of an event with consequences of different categories (no 8). Guidelines were considered important as they create consistency, which was identified to be lacking in practice by some interviewees. Nevertheless, some interviewees mentioned that standardized guidelines can become too rigid and not relevant for a specific analysis. Therefore, they may not be necessary as long as handling of scenarios with different dimensions is clearly agreed upon beforehand. Potential guidelines could cover topics such as for instance which type of consequence is being assessed (worst case, most credible etc.) in line with recommendation 11, as it was unclear for some interviewees which consequence was actually applied to visualize results from the coarse risk matrix. There were also different mapping philosophies provided by the interviewees. Some mapped consequence prior to likelihood or the other way around. The frequency mapped also differed. In some cases, interviewees mapped the frequency of an initiating event (e.g., closure of valve), whereas some mapped the frequency for the full scenario (e.g., closure of valve leading to overpressure upstream and explosion). Others mapped both frequency of the full scenario without safeguards, and then adjusted the frequency considering safeguards.

Not having a large variety of risk matrices within the same company and industry without motivation (no 13) was also deemed necessary and this recommendation was hence met with a generally positive attitude. A lot of different matrices had been seen by several interviewees without motivation. In some cases, the risk matrix had simply been updated based on trends. Many irrelevant risk matrices had also been seen by the interviewees, for instance where risk matrices for process industries had been copied from the healthcare sector with completely irrelevant elements.

Negative attitudes were generally expressed towards recommendations that increased complexity of the risk matrix and increased time requirements for a coarse risk analysis. These were recommendations such as adding more dimensions to the risk matrix (no 4), using a continuous PCDS (no 2), extending axes with more categories through the SUA method (no 3) or extending axes to counter centring bias (no 7) as well as showcasing uncertainty with e.g., prediction intervals (no 5). According to the interviewees, adding more dimensions and creating e.g., a 3D graph would increase complexity and decrease user friendliness when it comes to showcasing results. Having a continuous PCDS, increasing categories or adding prediction intervals would take more time as more categories or precise values/intervals have to be assessed during a coarse risk analysis.

However, prediction intervals were also said to have the possibility to reduce required time of the analysis, as disagreements during the workshop could be solved by getting "one end" of the interval each. Further, their value could be high for showcasing the most critical results from a QRA (i.e., not a coarse risk analysis), even if this is out of scope for the thesis. Nevertheless, some interviewees mentioned that a prediction interval would not provide any practical benefits, as the most conservative value would be assigned in practice. Hence, if an interval crosses two cells in the matrix, the cell with the highest risk would be chosen to represent the scenario. It shall however be noted that if a prediction interval is disregarded, it will not be possible to assess whether one scenario is more uncertain than another (having a larger prediction interval). Regardless, it was still deemed important by many of the interviewees to capture uncertainty in some way. Therefore, some interviewees did not directly neglect the idea of adding a third axis showing strength of knowledge, prediction intervals or other ways of showcasing uncertainty. Some interviewees were of the opinion that aforementioned is already captured by the width of cells in the matrix.

Some interviewees confirmed centring bias from experience, whilst others did not. It shall be noted that a bias might be subconscious, therefore simply asking about it might not confirm or deny its presence. Regarding the recommendation of extending axes to counter it, this was not considered a solution to the problem, as scenarios would still be placed in the middle of the now extended risk matrix. It was also identified to have the potential of giving false results (putting a scenario in a cell that is just an extension created to cater for centring bias and is actually not a reasonable consequence or frequency given the context). Further, those who did not see the potential for false results, still noted that adding cells to the matrix would increase time and complexity. Hence, the recommendation was met with a generally negative attitude. It shall however be noted that an extension of axes can actually counter for centring bias as per Duijm (2015) even though the interviewees might have been of another opinion.

Interviewees also voiced negative attitudes towards recommendations that were said to increase uncertainty. Therefore, calibration of the matrix based on expected number of scenarios leading to the same hazard (no 15), was deemed to increase uncertainty as the number of scenarios to calibrate for prior to the analysis was considered uncertain. Some stated that the matrix should only be used for assessing individual scenarios one at a time. Identifying systemic risk with the risk matrix was seen as an inherent limitation of the tool and therefore this recommendation was not considered relevant. However, there were a few interviewees who mentioned that if the

calibration can be done efficiently and the systemic risk can be captured – it could be an improvement of the matrix.

For some recommendations, there was no consistent opinion expressed. Transforming qualitative axes to quantitative (no 14) was a recommendation where some preferred quantification, whilst some preferred more detailed qualitative descriptions. However, those who preferred quantification were still of the opinion that a good qualitative description would be as good as a quantitative one – just not their personal preference. Further, some interviewees put forward the opinion that quantitative description may give an impression of results being more certain than they are. Regardless, all mentioned that the most important thing is that categories are well defined and not subjective (e.g., "major" consequences need to be described either in numbers or clearly with words as e.g., "minor injury handled by general practitioner").

For most interviewees, there was no clear answer or opinion given with regards to having the decision maker's attitudes guide the acceptance level (no 1). However, some interviewees presented a strong opinion that the decision maker's attitudes should be reflected in the acceptance level – on the premise that they are in line with best industry practice. Some of the interviewees said that there was some input given by decision makers (or client) in the risk matrix, while others expressed the opinion that this was not necessary as long as the matrix corresponded to best industry practice. Further, most interviewees stated that there was no practical need to provide guidelines for prioritization of scenarios in the same position in the matrix (no 9). Interviewees mentioned that scenarios in the same position should all be followed up in the same way. Nonetheless, some interviewees stated that a prioritization is made in reality based on either consequence category (e.g., scenarios with high health and safety consequences are more prioritized than scenarios with high financial consequences) or which scenario is easier to follow-up on. Interviewees mentioned that it should be noted that this prioritization is not part of any guideline, but still occurs in practice. Therefore, some interviewees considered it valuable to provide guidelines on prioritization of scenarios within the same cell so that it is done uniformly. This guideline could state that scenarios in the same cell shall be handled equally.

When it came to limitations, all interviewees were aware of some limitations with the risk matrix, as everyone mentioned at least one limitation as per recommendation no 10. Looking at all answers, all limitations stated in the literature with regards to Recommendation 10 were covered.

Finally, some interviewees proposed their own recommendations. These are given below:

- *Proposition to have anonymous risk analyses/workshops where participants can vote on the risk ranking to get a fair representation of intervals if these are to be used.*
- *Most scenarios are placed in yellow/ALARP region in the risk matrix; hence colouring could be done afterwards to decrease potential colouring bias.*
- *Proposition to not show the matrix during the workshops to counteract biases. Instead, assigned consequence and frequency can be added to a matrix afterwards. There might be difficulties with "openly" assessing these things without categories. This can be counteracted by asking "does this occur more often than 1 per 100 years" and if "yes" than "more often than 1 in 10 years" .*
- *Proposition from several interviewees to have a rule-set for handling scenarios with several consequence categories (i.e., if safety level 2 - always reputation level 1 etc.) as this decreases time and makes it easier to assess all consequence categories of a scenario.*

6. Proposed Recommendations

The assessment of which recommendations from Chapter 3.3 were considered practically suitable in a coarse risk analysis context, was performed by jointly studying the documentation and answers provided from the interviews. As mentioned in Chapter 1.4 Limitations, it shall be noted that the recommendations will solely be based on, and provided by, the scoping review. Therefore, any personal improvement suggestions from the writers/interviewees will not be presented as proposed recommendations.

Six of the identified 15 recommendations from the litterature study were deemed suitable. For full details regarding the assessment of suitability for each given recommendation, reference is made to Appendix H Chapter 10.8.

6.1 Selected Recommendations

The identified suitable recommendations and a short motivation is presented below (including some citations from interviewees):

- Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. View the tool with scepticism in mind.
    - *Even though there was some awareness about limitations of the tool based on the interviews, the documentation study sometimes indicated otherwise as conclusions were based on the risk ranking in the matrix. Furthermore, all limitations may not be known by each assessor and decision maker, making the recommendation suitable so that all limitations are properly captured. The recommendation also does not affect necessary time in the workshop/analysis (however, it may take some time before the analysis to inform all users and decision makers of the limitations and difficulties), complexity or user friendliness for the analysis which are deemed critical parameters for not implementing a recommendation according to the interviews.*

- Make the risk matrix more comprehensible through a few simple visual improvements provided in Figure 5:
    1. Use non-linear scale labelling for matrices with exponential or otherwise non-linear increase (i.e., having likelihood levels labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the levels labelled as 1,2,3,4).
    2. Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each level increases).
    3. Integrate information directly into the risk matrix instead of using legends (under the assumption that the risk matrix will not become too cluttered).
    - *All identified matrix types from the documentation study in Chapter 4 could benefit from some of the visual improvements as per this recommendation (e.g., type 2 is the only matrix benefitting with regards to removal of legends).*

None of the identified matrices from the document study had all potential visual improvements.
- *The recommendation was also deemed suitable and practically implementable according to what was identified in the interviews.*
- *"I am positive to visual aids and can see that it is practically possible to implement. "*
- *"...this adds value to the matrix and will make the matrix more clear."*
- *The recommendation also does not affect necessary time for risk assessment in the coarse risk analysis workshop, increase complexity nor decrease friendliness, which are deemed critical parameters for not implementing a recommendation according to the interviews.*

- Provide guidelines on the use of the risk matrix in case of an event with several categories of consequences (e.g., scenarios with consequences for both health, environment and financial). Be clear on which consequence is being mapped (e.g., worst case, most likely etc.).
    - *Even though it seemed from documentation that handling scenarios with several consequence dimensions in a HAZOP and LOPA was clear, guidelines were deemed very important and should therefore be issued according to the interviews.*
    - *The guidelines can cover e.g., which consequence category (s) is assessed (e.g., only looking at financial consequences).*
    - *The guidelines can cover which consequence will be assessed (e.g., the worst case or most likely one), as this was unclear for some of the interviewees.*
    - *The guidelines do not need to be general and can instead be suitable for the specific case and in accordance with the client or company - i.e., not necessarily standardized.*
    - *"Guidelines should always be provided. Before the analysis begins, guidelines should be stated so that people know how to manage scenarios with different dimensions of consequences."*
    - *"...I cannot answer how the assessment is made and which consequence is assessed."*
    - "*...It is unclear to me which consequence is assessed. Most likely it is worst case, but I actually don't know. Being clearer with regards to which consequence is assessed is an improvement for the use of the matrix.*"

- Clarify how risks that have the same score/position in the matrix should be prioritized.
    - *Based on documentation it did not seem valuable to apply this recommendation. This is because when risks are prioritized, they are done so based on colour only. Therefore, it would not be of value to e.g., clarify how two scenarios with the same score in a yellow cell are distinguished since they would both be taken from HAZOP to LOPA in practice or valued equally in a HAZID.*
    - *However, some interviewees state that prioritization is made in reality based on consequence category (e.g., impact on financial aspects is not as prioritized*

as impact on health or environment) and on how easy it is to decrease the risk for the scenario.
    - *"...it is done in practice already even if the intention might be to handle those scenarios in the same way. It is important to prioritize uniformly and therefore I think guidelines are important."*
    - *There were no guidelines available for how this prioritization is done but it still occurs in practice. Further, the recommendation does not increase complexity, uncertainty, or time necessary for the risk analysis workshop – it is therefore deemed suitable in order to increase uniformity in how prioritization is made.*

- Establish the risk matrix with decision maker's risk appetite in mind.
    - *It was not possible to assess from the documentation alone if the acceptance levels reflected decision maker's attitudes.*
    - *There was no clear answer or opinion given in the interviews and there were some contradicting answers given.*
    - *Some of the interviewees said that there was input given by decision makers (or client) with regards to risk acceptance levels, while others expressed the opinion that this was not necessary as long as the matrix corresponded to best industry practice.*
    - *Some interviewees presented a strong opinion that the decision maker's attitudes should be reflected in the acceptance level – on the premise that they are in line with best industry practice.*
    - *"It is very important that acceptance levels are based on best industry practice and that the managers etc. agree with this."*
    - *As it was not clear that decision maker attitudes were most often considered in practice, the recommendation is deemed necessary.*
    - *As consideration of decision maker attitudes was done for some matrices as identified in the interviews, it is considered enough evidence that the recommendation is also practically applicable.*

- Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix.
    - *From the documentation study in Chapter 4, it did not seem necessary to provide this recommendation, as mostly unified/standardized matrices within a company were identified (i.e., no large variety of matrices).*
    - *However, based on the interviews, it was clear that a large variety of risk matrices were actually present.*
    - *Furthermore, the varied matrices did not always have a motivation for why they had been used and created (sometimes they were simply "copy-pasted" from another industry or updated based on trends) according to the interviewees.*
    - *"Sometimes irrelevant risk matrices are used. I have seen things such as workplace environment risk matrices for a process safety assessment. Some*

elements become irrelevant in this case. There is sometimes a lack of motivation for the use of certain risk matrices."

- *The recommendation is hence deemed necessary based on the vast unmotivated amount of risk matrices. The recommendation also does not affect necessary time, complexity or user friendliness for the analysis which are deemed critical parameters for not implementing a recommendation according to the interviews.*

6.2 Dismissed Recommendations

The 9 recommendations which were dismissed were done so based on the following characteristics:

- Recommendations 2,3,4,7 & 15 were dismissed as they were not practical in a workshop setting due to time constraints (e.g., Adding even more cells or assessing uncertainties in a detailed manner increases necessary coarse risk analysis time).
- Recommendations 2,3,4 &7 were dismissed as they made the matrix too complex and decreased user friendliness (e.g., third axis, continuous scales etc.).
- Recommendation 15 was also dismissed as it brought forward even more uncertainty (e.g., introduction of new parameters with their own uncertainty or calibrating based on presumed number of scenarios introduces new uncertainties).
- Recommendation 5 & 14 were dismissed as they were considered to not be beneficial as other easier means could be used for the same purpose (e.g., clear qualitative descriptions instead of transforming axis to quantitative ones).
- Recommendation 7 was dismissed as it could actually skew results in an undesirable way (e.g., extending axis with values that are not relevant).
- Recommendation 11 was dismissed as it was incorporated into the guidelines provided by Recommendation 8.

7. Discussion

This chapter aims to elaborate on the meaning and significance of the proposed recommendations in relation to what is already known about the research problem. Additionally, the chapter aims to investigate the methodology, its limitations and how potential choices may have affected the outcome of the thesis.

7.1 Selected Recommendations

From what has been identified in the interviews and actual documentation of which risk matrices were used in "real life", it is fair to assume that the simplicity and user friendliness of the tool should not be compromised. This is in line with Cox (2008) mentioning that the tool is praised for its simplicity in the corporate world. Preservation of simplicity, user friendliness and time efficiency (in workshops) were factors deemed crucial when it came to application of the tool as part of visualizing results from coarse risk analyses. Therefore, recommendations increasing complexity, uncertainty or analysis time were dismissed and not deemed suitable. For example, simple visual improvements were deemed suitable as they do not compromise analysis time and matrix complexity whilst increasing user friendliness. It is important to note that the result may have been affected by the fact that the risk matrices and interviewees were identified in relation to coarse risk analyses as stated in the limitations in Chapter 1.4 and research question 2 and 3. In other words, other recommendations could have been deemed suitable if the matrix was used to present results from another type of analysis. This might indicate that these results are not generalizable for risk matrices in all contexts, but rather for risk matrices as part of illustrating results from coarse risk analyses. It shall however be noted that excessive simplifications are part of the provided critique by Flage and Røed (2012).

Further, opinions were raised during the interviews with regards to the necessity for increasing consistency of the use of the risk matrix by adding guidelines, as well as not using irrelevant risk matrices. It shall therefore be noted that if the risk matrix and its use become too simplified, consistency might be lost, and a potential irrelevant matrix might be used because it is simple. These findings during the interviews should be balanced with one another. On one hand, adding too much complexity to the matrix and increasing the required time in a coarse risk analysis is not seen as favourable. On the other hand, simplifying things so far that consistency is lost, or using a simple risk matrix without thought and relevancy to the context should also be avoided. It shall also be noted that none of the identified recommendations form the litterature contribute to making the risk matrix simplified, but when it comes to the selection of practically suitable recommendations, the importance lies in choosing such recommendations that do not contribute to increased complexity.

Overall, from the scoping review, it was clear that there were many different theoretical recommendations for improvement of the risk matrix. However, as stated by Flage & Røed, (2012) and Duijm (2015) there is limited research on guidance on the use of the risk matrix. One possible explanation for this may be that the recommendations are fairly new (most articles published from 2015 and onwards). This might explain why these have not become part of any actual guidance.

Six of the identified 15 recommendations summarized from the literature review were deemed suitable, which is perhaps a sign that theoretical recommendations for improvement are most often *not* suitable to implement. This may be either due to the limitations of the practical application of the tool or simply that the recommendations are not relevant for the specific context of the thesis.

The majority of the identified suitable recommendations deal with increasing awareness of uses and misuses of the tool. This can be either with regards to why a specific risk matrix is used, the limitations and difficulties of the tool, or how the tool is used (e.g., how to handle scenarios with several consequence categories). This may indicate that the tool has been used without much thought and research, which could be due to its simplicity or lack of guidance. This is consistent with what has been stated by Flage and Røed (2012). From the identified suitable recommendations and what has been stated in the interviews, it seems like there is a need for more awareness and guidance, even if the tool itself is simple. In a broader sense, regardless of how the recommendations are received (e.g., which consequence is chosen to be assessed), one can assume that a generally increased awareness would lead to a more consistent use of the matrix during an analysis and thus a more consistent visualization of the results.

In addition to opinions on the recommendations, some of the interviewees also presented their own suggestions for improvements. These are given in detail in Chapter 5.3. This might indicate that there is some interest for this topic, and that those using the matrix have thought about possible improvements themselves already. It shall be noted that some interviewees presented the exact same recommendation. The fact that several interviewees proposed the same improvement might indicate that guidance can be given not only based on theoretical recommendations from literature, but also from those using the matrix on a day-to-day basis. Worth noting is that some of the proposed recommendations deal with some of the identified critique of the matrix. For instance, the proposition to not assign colour to the matrix during the risk analysis might deal with the critique presented by Flage & Røed (2012) mentioning that colouring might take the focus away from the scenario and on to mechanistic decision making as discussed in Chapter 2.

7.2 Scoping Review

There were limitations and weaknesses with the scoping review partially derived from the search string used. What was supposed to be a very open research question, became a limitation through the choice of the term "guidelines" in the search as hits had to include terms linked to "risk matrix", "criticism", “improvement" *and* "guidelines” This requirement that all terms should appear simultaneously may have meant that articles that could have been relevant had been excluded as they might have covered “criticism”, “risk matrix” and “improvement” but not “guidelines”. The reason for emphasizing the word guidelines was because it was part of our research question in the scoping review, as well relating to the goal of added guidance from the thesis. However, it was later identified that this might be an unnecessary restriction. In order to try to reduce the impact of this restriction in the search string, the reference analysis was performed to capture any relevant literature not identified due to the chosen search string.

Furthermore, a search was made in Scopus with a revised search string where terms linked to "risk matrix" would appear together with terms linked to *either* "guidelines" *or* "improvement" together with terms linked to "criticism" as following:

("Risk matri*" OR "Risk Diagram") AND (guidelines OR framework OR standard* OR improv* OR better* OR uplift) AND (critique OR criticism OR review)

The search was done with the criterion that the risk matrix would be a keyword and the article should be in English. This yielded 184 hits in Scopus compared to the previous 98. Upon a quick review of the titles, the assessment was that with a broader search string yielding more hits, the hits were not necessarily more relevant to the thesis compared to the hits in the first search.

It was further noted that the hits given after applying the inclusion criteria of "keyword" and "English" were quite few compared to what could be expected. The reason for having the inclusion criteria of risk matrix being a keyword in the search, was that without it, many of the hits yielded articles that contained "risk matrix" but touched on many other topics. This was identified even with the applied restriction. With the requirement for a keyword, many hits were filtered out and there were more hits left with articles explicitly covering the topic of risk matrices.

Furthermore, there are more synonyms to risk matrix that could have been covered in the search string apart from "risk matri*" and "risk diagram". For instance, the term probability consequence diagram (PCDS) is used to some extent and not covered in the search string. An initial scan of the articles from the search could have provided knowledge of terms alternative to ones used in the search. As this was not performed, potential literature covering PCDS might have been missed.

Finally, as the overall aim of the thesis is to provide recommendations, this keyword would be reasonable to add as a synonym to guidelines. However, as the thesis has been an iterative process, the focus at the beginning was on providing guidelines – i.e., *information intended to advice on how something should be done* (Cambridge Dictionary). Further on, it was realized that the thesis does not intend to advice but rather *recommend* – i.e., *suggest something suitable to a particular situation* (Cambridge Dictionary). With this in mind, the synonym of recommendation was unfortunately missed due to iterative nature of the process. It should however be mentioned that a wide array of literature covering recommendations was identified even though guidelines were used as part of the search string.

In summary, the not fully optimized scoping review gave a result relevant to the research question and the purpose of the thesis as a whole.

7.3 Documentation

When it comes to limitations and possible improvements regarding the studied documentation, one theme to discuss is the fact that only one company (ORS) provided the documentation. This might be a limiting factor as other companies might have provided other risk matrices, giving a broader view of the "practical use". However, the project archive of ORS Consulting was chosen due to their extensive experience in using risk matrices as part of coarse risk analyses together with their broad client base. Hence, many different risk matrices were still identified, as ORS performs risk analyses for a wide array of clients. Oftentimes, ORS is requested to use the corporate or otherwise provided risk matrix by the client which contributes to the variety and good insight into the practical applications. Furthermore, as ORS had high availability and were able to provide resources for identifying risk matrices, it was deemed that their project archive and input would be sufficient to cover the scope of research question 2.

Another limiting factor is that the industries in which the matrices are used could have been broader to reflect a broader practical application. The matrices studied to produce the generic risk matrices were mainly from the oil and gas or chemical industry. However, the number of matrices and their use was still deemed adequate to get an answer to research question number 2, as *various* industries and a wide array of different matrices were identified.

Finally, confidentiality was a limiting factor when it came to showing the identified risk matrices. This due to the fact that the identified risk matrices could not be revealed directly. This was handled by creating generic matrices. With this in mind, the ability to recreate or correctly capture all features of the identified risk matrices might constitute a source of error or limitation. This was counteracted by presenting the risk matrices in as much detail as possible (without showcasing or giving out the company name) in Appendix D Chapter 10.5. With this, the reader can verify that the generic risk matrices correctly capture all features. Furthermore, it can be argued that through the creation of generic risk matrices, a first step of analysis is performed where a wide array of risk matrices are generalized into categories for which different recommendations may apply. Since the task was to identify relevant recommendations for improving risk matrices in the context of coarse risk analyses, it can be a strength to produce general matrices based on identified characteristics of existing matrices. Otherwise, the thesis could result in proposals for the improvement of some specific matrices which would decrease its generalizability.

7.4 Interviews

The first interviews were conducted with ORS personnel. This meant that these people were known by the interviewers prior to conducting the interviews. Therefore, adjusting to personality and creating an environment where the interviewee could speak freely and express themselves about experiences and opinions on a topic was made easier. This made the interviewers more comfortable with the interviewing of previously unfamiliar people further on in the process, as any mistakes performed in the beginning could be adjusted for further on. For instance, a shorter follow-up was made the following day with interviewee nr 1 to clarify a couple of the answers and ask a couple of follow-up questions which were missed during the initial first interview. This was corrected in all following interviews. On the other hand, the interviews were reviewed, and technique was improved through the process, which means that interviews conducted later on were done so with more confidence and better execution, potentially counteracting the fact that the interviewees were unknown from previously.

The interviews were highly affected by the personality of the interviewee. Some could hold very long explanations that took time and where the answer to the question was difficult to decipher. Others were very particular in their answers and had difficulties to present an opinion for the posed question. This may have affected the results and capturing of their opinions.

The interviews covered all questions and gave thorough enough answers as input to the thesis. However, time was a limiting factor for some interviews, where all questions could not be covered. With this in mind, some crucial answers could be missed, and results skewed. It shall be noted that the following only occurred for 1 out of 10 interviews.

7.5 Further Studies

As the thesis is purely theoretical, the identified recommendations were not possible to test in practice. Hence, the result of actually implementing the proposed recommendations could have been studied further to give a broader insight into how the use of the risk matrix is affected by applying the recommendations. One way of studying this can be by considering the provided recommendations and let two groups risk rank and map some given scenarios. Further, two other groups can risk rank and map the same scenarios, but without considering the recommendations. If the two groups which considered recommendations risk rank and map the scenarios more alike than the groups without provided recommendations – it may be an indication that the recommendations actually increase consistency and hence improve the use of the risk matrix.

The majority of the identified suitable recommendations deal with increasing awareness of uses and misuses of the tool. Therefore, it would have been interesting to investigate whether the quality of the results of the use of the risk matrix increases in correlation with increased awareness of .e.g., limitations. This could be done by studying whether the results plotted in a risk matrix from a coarse risk analysis are deemed better after implementation of recommendations dealing with increased awareness. For instance, the same group can do a HAZID not considering the provided recommendations, and then re-do it considering the recommendations comparing the results and whether they consider them to have been improved.

Several of the interviewees provided suggestions of their own as shown in Chapter 5.3 which was outside of the scope for this thesis. It might however be of interest to further study and identify potential recommendations for improving the tool provided by people using them as part of their profession.

As mentioned previously, the result may have been affected by the fact that the risk matrices and interviewees were most often identified in relation to coarse risk analyses. Other recommendations could therefore have been deemed suitable if the matrix was in the context of another type of analysis. This can be of interest to study further.

8. Conclusions

The purpose of the thesis was to add to the currently limited guidance on the use of the risk matrix, considering suitability to its wide practical application in coarse risk analyses. This was done by providing answers to the following three research questions:

1. Which recommendations are provided for optimizing the use of the risk matrix in theory?

From the scoping study, 15 unique recommendations for improvement of the risk matrix were identified. These covered different aspects. For instance, there were recommendations for both visual changes (e.g., adding a third axis or removing legends) as well as increased awareness of uses and misuses of the tool the tool (e.g., providing guidelines on the use of risk matrix in case of an event with several categories of consequences, being aware of the limitations of the tool etc).

2. How is the risk matrix designed and used in practice in the context of coarse risk analyses?

From the study of the project archive and client standards from ORS Consulting, 16 unique risk matrices were identified. Further it was identified in what type of coarse risk analysis the matrix was used. Based on similar characteristics of the risk matrices, four representative risk matrices were created capturing common features.

As part of visualizing the results from a coarse risk analysis, the risk matrix position of an identified scenario in the coarse risk analysis was in practice oftentimes decided upon in a workshop setting. The position in the matrix could guide whether a scenario should be further studied in for instance a LOPA or describe if the design was overall deemed acceptable/alternative design should be considered.

3. How will the implementation of the theoretical recommendations work in practice and which ones are suitable to implement in the context of coarse risk analyses for various industries?

Through the identified matrices and their use, it was possible to perform a first assessment with regards to the suitability of the 15 recommendations identified in the scoping review. The answers provided from interviews further studied the opinions of the interviewees with regards to the 15 recommendations and their potential practical limitations.

The assessment of which theoretical recommendations were considered practically suitable was performed by jointly studying the documentation and answers provided from interviews. Preservation of simplicity, user friendliness and time efficiency were factors deemed crucial when it came to the application of the tool as part of visualizing results from coarse risk analyses. Therefore, recommendations increasing complexity, uncertainty or workshop time were dismissed and not deemed suitable. For example, simple visual improvements were deemed suitable as they do not compromise workshop time and complexity whilst also increasing user friendliness. It shall however be noted that excessive simplifications are part of the critique provided of the tool. Therefore, an excessive simplification may not be beneficial.

Furthermore, opinions were raised during the interviews with regards to the necessity for increasing consistency of the use of the risk matrix by adding guidelines, and not using irrelevant risk matrices. There is a potential that if the risk matrix and its use become too simplified, consistency might be lost, and potential irrelevant matrices might be used with the motivation that they are considered simple. On one hand, adding too much complexity to the matrix and increasing the required time in a coarse risk analysis is not seem as practically suitable with regards to improving the use of the tool. On the other hand, simplifying things so far that consistency is lost, or a risk matrix is used without thought and relevance to the context should also be avoided. It shall also be noted that none of the identified recommendations form the litterature contribute to making the risk matrix simplified, but when it comes to the selection of practically suitable recommendations, the importance lies in choosing such recommendations that do not contribute to increased complexity.

With the following in mind, the 15 recommendations were hence narrowed down the to the following six recommendations deemed suitable:

- Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. View the tool with scepticism in mind.
- Make the risk matrix more comprehensible through a few simple visual improvements (e.g., increase cell size logarithmically if the scale is logarithmic)
- Provide guidelines on the use of the risk matrix in case of an event with several categories of consequences (e.g., consequences for both health, environment and financial) and be clear on which consequence that is mapped (worst case, most likely etc.)
- Clarify how risks that have the same score/position in the matrix should be prioritized.
- Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix.
- Establish risk matrix with decision makers risk appetite in mind.

With the above selected recommendations, the purpose of the thesis has been fulfilled – i.e., adding to the currently limited guidance on the use of the risk matrix, considering suitability to its wide practical application for illustrating results of coarse risk analyses. With the identified suitable recommendations, the gap between theoretical recommendations for improving the use of the matrix and the practical possibility to implement those, has been bridged.

9. References

Ale, B., Burnap, P., Slater, D., (2014) *On the origin of PCDS – (Probability consequence diagrams)*. Elsevier.

Amundrud, O., & Aven, T. (2012). *A practical guide on how to present and visualize the result of risk and vulnerability analyses in a societal safety and security context*. In I n Presented at the 11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference.

Aven, T. *Risk Analysis*. John Wiley & Sons, Incorporated, 2015. ProQuest Ebook Central, http://ebookcentral.proquest.com/lib/lund/detail.action?docID=4739940.

Aven, T. (2017). *Improving risk characterisations in practical situations by highlighting knowledge aspects, with applications to risk matrices*. Reliability Engineering & System Safety, 167, 42–48. https://doi.org/10.1016/j.ress.2017.05.006

Arksey, H., & O'Malley, L. (2005). *Scoping studies: towards a methodological framework*. International Journal of Social Research Methodology, *8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Ball, D. J., & Watt, J. (2013). *Further thoughts on the utility of risk matrices: Utility of risk matrices*. Risk Analysis: An Official Publication of the Society for Risk Analysis, 33(11), 2068–2078. https://doi.org/10.1111/risa.12057

Bao, C., Wu, D., Wan, J., Li, J., & Chen, J. (2017). *Comparison of different methods to design risk matrices from the perspective of applicability*. Procedia Computer Science, 122, 455–462. https://doi.org/10.1016/j.procs.2017.11.393

Baybutt, P. (2015). *Calibration of risk matrices for process safety*. Journal of Loss Prevention in the Process Industries, 38, 163–168. https://doi.org/10.1016/j.jlp.2015.09.010

Baybutt, P. (2016). *Designing risk matrices to avoid risk ranking reversal errors*. Process Safety Progress, 35(1), 41–46. https://doi.org/10.1002/prs.11768

Baybutt, P. (2018). *Guidelines for designing risk matrices*. Process Safety Progress, 37(1), 49–55. https://doi.org/10.1002/prs.11905

Beerens, R. J. J., & Tehler, H. (2016). *Scoping the field of disaster exercise evaluation - A literature overview and analysis. International Journal of Disaster Risk Reduction*: IJDRR, 19, 413–446. https://doi.org/10.1016/j.ijdrr.2016.09.001

Bolbot, V., Theotokatos, G., McCloskey, J., Vassalos, D., Boulougouris, E., & Twomey, B. (2022). *A methodology to define risk matrices – Application to inland water ways autonomous ships*. International Journal of Naval Architecture and Ocean Engineering, 14(100457), 100457. https://doi.org/10.1016/j.ijnaoe.2022.100457

Brinkmann, S., & Kvale, S. (2014). *InterViews: Learning the craft of qualitative research interviewing* (3rd ed.). SAGE Publications.

Bryman, A. (2018). *Samhällsvetenskapliga metoder* (3rd ed). Liber.

Cambridge dictionary. (n.d.). Cambridge.org. Retrieved January 16, 2023, from https://dictionary.cambridge.org/

Cox, L. A., Jr. (2008). *What's wrong with risk matrices?* Risk Analysis: An Official Publication of the Society for Risk Analysis, *28*(2), 497–512. https://doi.org/10.1111/j.1539-6924.2008.01030

Crawley, F. (2020). *A guide to hazard identification methods A guide to hazard identification methods (2nd ed.)*. Elsevier Science Publishing. https://doi.org/10.1016/C2018-0-05378-5

Daudt, H. M. L., van Mossel, C., & Scott, S. J. (2013). *Enhancing the scoping study methodology: a large, inter-professional team's experience with Arksey and O'Malley's framework*. BMC Medical Research Methodology, 13(1), 48. https://doi.org/10.1186/1471-2288-13-48

Duijm, N. J. (2015). *Recommendations on the use and design of risk matrices*. Safety Science, 76, 21–31. https://doi.org/10.1016/j.ssci.2015.02.014

Elmontsri, M. (2014). *Review of the strengths and weaknesses of risk matrices*. Journal of Risk Analysis and Crisis Response, 4(1), 49. https://doi.org/10.2991/jrarc.2014.4.1.6

Flage, R,.& Røed, W,. (2012). *A Reflection on Some Practices in the Use of Risk Matrices.*

Gerson, K., & Damaske, S. (2020). *The Science and Art of Interviewing.* Oxford University Press. doi:10.1093/oso/9780199324286.001.0001

Gibson, W., & Brown, A. (2009). *Working with Qualitative Data*. SAGE Publications.

Guest, G., E. Namey, E., & L. Mitchell , M. (2013). *Collecting Qualitative Data: A Field Manual for Applies Research*. SAGE Publications, Ltd.

Goerlandt, F., & Reniers, G. (2016). *On the assessment of uncertainty in risk diagrams*. Safety Science, 84, 67–77. https://doi.org/10.1016/j.ssci.2015.12.001

Hong, Y., Pasman, H. J., Quddus, N., & Mannan, M. S. (2020). *Supporting risk management decision making by converting linguistic graded qualitative risk matrices through interval type-2 fuzzy sets*. Process Safety and Environmental Protection : Transactions of the Institution of Chemical Engineers, Part B, 134, 308–322. https://doi.org/10.1016/j.psep.2019.12.001

Hora, S. C. (2007). *Eliciting probabilities from experts.* In W. Edwards, R. F. Miles Jr, & D. von Winterfeldt (Eds.), Advances in Decision Analysis (pp. 129–153). Cambridge University Press.

Höst, M., Regnell, B., & Runesson, P. (2006). *Att Genomföra Examensarbete*. Lund: Författarna och Studentlitteratur.

ISO/IEC 31010:2019 *Risk management - Risk assessment techniques.*

Kaya, G. K., Ward, J., & Clarkson, J. (2019). *A review of risk matrices used in acute hospitals in England: Risk matrices used in acute hospitals*. Risk Analysis: An Official Publication of the Society for Risk Analysis, 39(5), 1060–1070. https://doi.org/10.1111/risa.13221

Levine, E. S. (2012). *Improving risk matrices: the advantages of logarithmically scaled axis*. Journal of Risk Research, 15(2), 209–222. https://doi.org/10.1080/13669877.2011.634514

Levac, D., Colquhoun, H., & O'Brien, K. K. (2010). *Scoping studies: advancing the methodology*. Implementation Science: IS, 5(1), 69. https://doi.org/10.1186/1748-5908-5-69

Li, Z. P., Yee, Q. M. G., Tan, P. S., & Lee, S. G. (2013). *An extended risk matrix approach for supply chain risk assessment*. 2013 IEEE International Conference on Industrial Engineering and Engineering Management.

Li, J., Bao, C., & Wu, D. (2018). *How to design rating schemes of risk matrices: A sequential updating approach*. Risk Analysis: An Official Publication of the Society for Risk Analysis, 38(1), 99–117. https://doi.org/10.1111/risa.12810

Markowski, A. S., & Mannan, M. S. (2008). *Fuzzy risk matrix*. Journal of Hazardous Materials, 159(1), 152–157. https://doi.org/10.1016/j.jhazmat.2008.03.055

National Patient Safety Agency. (2008). *A risk matrix for risk managers*.

Ni, H., Chen, A., & Chen, N. (2010). *Some extensions on risk matrix approach*. Safety Science, 48(10), 1269–1278. https://doi.org/10.1016/j.ssci.2010.04.005

ORS Consulting. (11th of November 2022). *Services.* https://www.ors-consulting.com/

Pascarella, G., Rossi, M., Montella, E., Capasso, A., De Feo, G., Botti, G., Nardone, A., Montuori, P., Triassi, M., D'Auria, S., & Morabito, A. (2021). *Risk analysis in healthcare organizations: Methodological framework and critical variables*. Risk Management and Healthcare Policy, 14, 2897–2911. https://doi.org/10.2147/RMHP.S309098

Peace, C. (2017). *The risk matrix: uncertain results?* Policy and Practice in Health and Safety, 15(2), 131–144. https://doi.org/10.1080/14773996.2017.1348571

Pickering, A., & Cowley, S. P. (2010). *Risk Matrices: implied accuracy and false assumptions*. Journal of Health & Safety Research & Practice, 2(01)), 11-18

Ruan, X., Yin, Z., & Frangopol, D. M. (2015). *Risk matrix integrating risk attitudes based on utility theory: Risk matrix integrating risk attitudes*. Risk Analysis: An Official Publication of the Society for Risk Analysis, 35(8), 1437–1447. https://doi.org/10.1111/risa.12400

Ruge, B. (2004). *Risk matrix as tool for risk assessment in the chemical process industries*. In Probabilistic Safety Assessment and Management (pp. 2693–2698). Springer London.

Semiquantitative risk matrix. (n.d.). Tamu.edu. Retrieved January 20, 2023, from https://wikips.tamu.edu/semiquantitative-risk-matrix/

Smith, E. D., Siefert, W. T., & Drain, D. (2009). *Risk matrix input data biases*. Systems Engineering, 12(4), 344–360. https://doi.org/10.1002/sys.20126

Sutherland, H., Recchia, G., Dryhurst, S., & Freeman, A. L. J. (2022). *How people understand risk matrices, and how matrix design can improve their use: Findings from randomized controlled studies*. Risk Analysis: An Official Publication of the Society for Risk Analysis, 42(5), 1023–1041. https://doi.org/10.1111/risa.13822

Tehler, H. (2020). *An Introduction to Risk and Risk Managemnt.* Division of Risk Management and Societal Safety, Lund University.

Thomas, P., Bratvold, R. B., & Eric Bickel, J. (2014). *The risk of using risk matrices*. SPE Economics & Management, 6(02), 56–66. https://doi.org/10.2118/166269-pa

Vatanpour, S., Hrudey, S. E., & Dinu, I. (2015). *Can public health risk assessment using risk matrices be misleading?* International Journal of Environmental Research and Public Health, 12(8), 9575–9588. https://doi.org/10.3390/ijerph120809575

Yi, C. J., Zheng, C. Y., & Fu, Q. H. (2013). *Improvement and application of risk matrix*. Applied Mechanics and Materials, 357–360, 2650–2654. https://doi.org/10.4028/www.scientific.net/amm.357-360.2650

Zhu, Q., Kuang, X., & Shen, Y. (2003). *Risk matrix method and its application in the field of technical project risk management*. Engineering Science, 5(1), 89-94.

10. Appendices

10.1 Appendix A - Coarse Risk Analysis Methods

Hazard and Operability (HAZOP) Study

Hazard and Operability (HAZOP) study is a systematic process where the analyst assesses existing hazards through brainstorming or workshop in order to identify and evaluate problems that may represent risks to either personnel, equipment, or environment. This is done through a systematic breakdown of a more complex system by splitting it into so called nodes. Each node is analysed separately to pick up issues that otherwise might not have been found (ISO 3101). The HAZOP focuses on events occurring due to the process.

The HAZOP methodology can be described as following (ISO 3101):

- The system is divided into nodes, i.e., a subsystem (e.g., from a separator inlet to a control valve)
- For each node, predetermined combinations of guidewords (such as more, less, none) and parameters (such as flow, temperature, pressure) are used to create a deviation from the design intent. For example, more pressure.
- Causes (i.e., scenarios) for each deviation are identified. E.g., causes for more pressure might be failure of a valve in a closed position.
- Consequences for each deviation are identified assuming all safeguards fail. E.g., overpressure of pipeline upstream the closed valve leading to loss of containment and damage to operators nearby.
- Safeguards for preventing the hazardous scenario from reaching its full potential are identified. E.g., a shutdown sequence initiating upon detention of the high pressure in the pipeline.
- **The scenario is potentially risk ranked with the use of a risk matrix.**
- Recommendations/Actions are provided for further mitigation or improvement.

The HAZOP method is a qualitative method performed by a multidisciplinary team by using standardized procedure guide words relevant for each node to identify risks and present solutions on how to manage the raised risks. HAZOP can be done both in the design stage of a process or carried out during operation (ibid).

Layers of Protection Analysis (LOPA)

The Layers of Protection Analysis (LOPA) is a semi-quantitative method to estimate consequences in connection to risk scenarios .The intention with the method is to decide if sufficient measures are taken to mitigate or manage the risk for a certain scenario. The LOPA is performed according to the following steps (ISO 3101):

- Initiating causes for a scenario are identified (through e.g., HAZOP) and data is collected with regards to their probability.
- Layers of protection/safeguards for the given causes of the scenario are identified (e.g., from HAZOP) and analysed for their effectiveness.
- Independent Protection Layers (IPLs) are identified (not all safeguards are independent) for each initiating cause.
- The probability of failure for each IPL is identified.

- Frequency of initiating causes for a scenario are combined with the probabilities of failure of each IPL protecting from the initiating cause for all causes of the scenario. Also, the probabilities of any conditional modifiers are regarded (this could be that operators are in the area only 50% of the time).
- The calculated level of risk/ the frequency of the scenario occurring (i.e.,. the combination of frequency of initiating causes and probability of failure of the safeguards) is compared to the risk tolerance.

Hazard Identification (HAZID)

Hazard Identification (HAZID) study differs from HAZOP in that it has more focus on consequences instead of cause. Also, external events are analysed (i.e., not only the process as in the HAZOP). Based on this, further measures can then be taken to minimize or mitigate the effect. Like HAZOP, guidewords are used in order to identify initiating causes of an event, but these are not as standardized as those for HAZOP, but cover a wider array of hazards (e.g., evacuation and rescue, helicopter lift, overtrawling) . The methodology otherwise follows the same as steps as described in Section 5.1.1 for the HAZOP (Crawley, F., 2020).

10.2 Appendix B - Inclusion and Exclusion Criteria

Inclusion Criteria	**Comment/Motivation**
● The literature should be in English	In order to understand and analyse the content, the full article has to be in English.
● Risk Matrix should be a keyword for the literature	The literature needs to explicitly cover the topic risk matrices, as there might be articles where the method risk matrix is used, while the article itself covers an irrelevant topic.
● The abstract and/or title implies that the risk matrix itself has been analysed as a tool.	As the research question and purpose of the thesis is to provide guidance on the use of risk matrices it is of interest to look at literature where the risk matrix has been discussed as a method or analysed as a tool.
● The abstract and/or title covers the usage of the risk matrix as a tool and proposes improvements through either altering the use of the risk matrix or presenting critique.	The research question and purpose of the thesis is to provide potential improvement and identify critique.
● The abstract and/or title covers the perception of risk matrices.	The perception of the risk matrix gives the possibility to evaluate potential improvement of the tool with regards to “human-risk matrix” interfaces.
Exclusion Criteria	**Comment/Motivation**
● The abstract and/or title implies that literature covers studies where risk matrices have been used as a tool with no further comments on the risk matrix itself.	As the research question and purpose of the thesis is to provide guidance on the use of risk matrices it is of interest to look at literature where the risk matrix has been discussed as a method - not only used as a tool in a case study.
● The abstract implies that the risk matrix is a part of a larger risk analysis tool with no further comments on the included method or risk matrix.	Many studies identified covered the risk matrix aspect, but only in the sense that the risk matrix was a part of a larger risk analysis or tool, where no emphasis was put on the risk matrix as a method. These types of studies were assumed to further not address any critique or potential improvement of the risk matrix method itself.
● The abstract did not correlate with the title with regards to inclusion criteria.	Some studies had titles that implied that the study should be included, however, once the abstract had been read it did not correlate with the title with regards to the risk matrix being analysed, critiqued, studied with regards to perception or improved upon.

10.3 Appendix C - Summary of Group 1 and Group 2 Litterature

Group 1 Studies

Title	Author	Year	Summary	Motivation for group 1 categorization + key points
How People Understand Risk Matrices, and How Matrix Design Can Improve their Use: Findings from Randomized Controlled Studies	Sutherland, H., Recchia, G., Dryhurst, S., Freeman, A.L.J.	2022	The study covers how risk matrices are perceived by people and how design choices have an impact. By making experiments it is showcased that the following design choices to the risk matrix can improve communication: ● Using non-linear scale labelling for matrices with exponential or otherwise non-linear increase (i.e., having likelihood categories labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the categories labelled as 1,2,3,4). ● Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each category increases) ● Integrating information directly into the risk matrix instead of using legends (under the assumption that the risk matrix	The article covers improvements of the risk matrix with regards to perception of the tool. The article presents the pros and cons of risk matrices and gives several suggestions for improvement when it comes to the design of the matrix, cell size, etc. A certain amount of analysis is also presented here regarding suggestions for future improvement, where they refer, among other things, to a study that shows that it is not intuitive to understand logarithmic axis.

Title	Author	Year	Summary	Motivation for group 1 categorization + key points
			will not become too cluttered).	
A Review of Risk Matrices Used in Acute Hospitals in England	Gulsum Kubra Kaya, James Ward, and John Clarkson	2019	The study is centred around the fact that other industries (not healthcare) have criticized the use of risk matrices, but the applicability of the criticism has not been investigated within healthcare. The study therefore examines risk matrices in acute hospitals in England and provides guidelines for their use. The study concludes that hospitals may not provide enough guidance on how to use the matrices and their inherent limitations. Furthermore, it is found that several different matrices are used without motivation behind them. Guidelines are given for the improvement of use of the risk matrix.	The study both addresses critique and provides improvement on the risk matrix as a tool. Guidelines for the use of risk matrix to simplify risk communication.
An Extended Risk Matrix Approach for Supply Chain Risk Assessment	Z. P. Li, Q. M. G. Yee, P. S. Tan, S.G. Lee	2014	The study covers advantages, limitations, and applications of the Risk Matrix Approach (RMA). The study purpose is to find ways to improve the applicability of the risk matrix as well as enrich the features of it. Specifically in supply chain risk management. The proposed improvement is a so-called extended risk matrix, where recoverability and detectability is added as metrics to the risk matrix to overcome limitations of the traditional 2D matrix. It is mentioned that the approach is not only limited to supply chain risk management but can be applied in other industries as well.	The study covers critique (i.e., limitations) and improvement of the risk matrix (in this case with a third axis representing detectability and recoverability).
Can Public Health Risk Assessment Using Risk Matrices Be Misleading?	Shabnam Vatanpour, Steve E. Hrudey, Irina	2015	The study investigates, through an experiment, the known problem when the frequency and severity of	The study presents criticisms and the shortcomings of the risk matrix and presents "soft" suggestions on how it can be used despite these, this should

Title	Author	Year	Summary	Motivation for group 1 categorization + key points
	Dinu		risks are negatively correlated, giving a misleading representation . The obtained risk from the experiential data was compared to estimates provided by the risk assessment matrix and the same results were obtained. The study points out that users of the risk matrix should be aware of this problem or at least contemplate whether there could be this type of negative correlation. Further, it is mentioned that the risk matrix assessment can be used to stimulate a valuable discussion, reflect on what can go wrong and how well prepared the organization is equipped to handle various risks. It is noted that risk matrix outputs should not be allowed to solely guide decision making.	then lead to increasing the usefulness of the risk matrix. It may be going in the wrong direction to strive to make the risk matrix as quantitative as possible and fill it with information. The way to go may instead be to change the way we see it as a simple way to communicate risk and visualize risk to create greater risk awareness. they can then be viewed with a healthy amount of scepticism
Improving risk characterisations in practical situations by highlighting knowledge aspects, with applications to risk matrices	Terje Aven	2017	The study mentions that one way of risk characterization is through the use of the risk matrix. The key, according to this study, is to better reflect the "knowledge" aspect of risk as this is not given by the current two-dimensional (probability and consequence) way of describing and presenting risk. Extended risk matrices are hence highlighted. It is stated that the two-dimensional risk matrix should not be used, but rather an extended matrix with an axis reflecting the strength of knowledge should always be added. Furthermore, consequences should be assessed as a spectrum by adding for	The study covers critique of the current risk characterization and risk matrix. Further, the study suggests improvements upon the risk matrix through the use of a third axis representing the strength of knowledge.

Title	Author	Year	Summary	Motivation for group 1 categorization + key points
			instance prediction intervals.	
On the assessment of uncertainty in risk diagrams	Floris Goerlandt, Genserik Reniers	2015	The study discusses the limitations and problems with the risk matrix. Especially, focus is on how to communicate uncertainty and represent it visually in the risk matrix. The study further discusses previously proposed methods for representing uncertainty together with shortcomings and merits. Finally, a proposal is made on how to better represent uncertainty in the risk matrix.	The study presents criticism and suggestions for methods to improve risk matrices. The study evaluates several other studies' suggestions for improvement and develops their proposed improvements into a new model.
Recommendations on the use and design of risk matrices	Nijs Jan Duijm	2015	This paper explores the weakness of the risk matrix and provides recommendations on the use and design of the risk matrix. Further, it emphasizes the previously given recommendations as well as adding new suggestions. The reviewed recommendations cover e.g., colouring of the risk, logarithmic scales, major accident aversion, use of corporate risk matrix standards. The study proposes a continuously scaled probability consequence diagram instead of having “discrete” cells.	Review of the risk matrix for deficiencies and comments on the results of other studies. The study presents suggestions for improvement through the use of a continuous probability consequence diagram with uncertainty presented through box width and length. The continuous diagram is described as an alternative to the risk matrix, but also simply a way of not assigning discrete categories. Hence, it is assumed to still be a risk matrix (just not a gridded one)
Risk Matrix Integrating Risk Attitudes Based on Utility Theory	Xin Ruan, Zhiyi Yin and Dan M. Frangopol	2015	The study covers the fact that risk attitudes are not considered during the establishment of a risk matrix. The study also discusses previous critique with regards to the risk matrix. An approach is proposed where risk attitudes are included during the	The study only covers the risk acceptance part of the risk matrix (i.e., uncertainties in probability and consequences are touched upon but said to be saved for other articles). The study discusses the limitations of the risk matrix and the lack of risk attitudes as part of the risk matrix. Further, the study proposes an improvement to the risk matrix with

Title	Author	Year	Summary	Motivation for group 1 categorization + key points
			establishment of a risk matrix. A complete risk matrix establishment process is introduced through decision makers' answers to questions in a questionnaire. The answers then formulate required boundary values for a risk matrix. Utility functions are used to quantify the risk attitudes.	regards to how the risk matrix should be developed by taking risk attitudes into account. The study both addresses critique and provides improvement on the risk matrix as a tool.
Risk Analysis in Healthcare Organizations: Methodological Framework and Critical Variables	Giacomo Pascarella, Matteo Rossi Emma Montella, Arturo Capasso, Gianfranco De Feo, Gerardo Botti Snr, Antonio Nardone Paolo Montuori, Maria Triassi, Stefania D'Auria, Alessandro Morabito	2021	This study gives an overview of the risk matrix with regards to critical variables, advantages, disadvantages, strengths, and weaknesses of this tool. The study summarized previously given critique by many other authors and highlights several recommendations provided by those authors.	The study both addresses critique and summarizes already given recommendations with regards to improvement on the risk matrix as a tool.
Supporting risk management decision making by converting linguistic graded qualitative risk matrices through interval type-2 fuzzy sets	Yizhi Hong, Hans J. Pasman⁎, Noor Quddus, M. Sam Mannan	2019	This study reviews some limitations and weaknesses to the risk matrix, especially with regards to risk matrices that have linguistically graded axis. For example, it is mentioned that it is difficult to compare or merge different results from different matrices in a company/ at a plant, as people tend to interpret words differently. The study proposes a way of quantifying linguistic terms through a second-generation fuzzy logic technique.	The study presents a thorough review of the limitations of the risk matrix. Furthermore, a development of a previous improvement strategy is presented where the concept of fuzzy-logic approach is further developed with type 2 fuzzy-logic. Hence, the study both presents critique and provides improvement to the risk matrix as a tool.

Group 2 Studies

Title	Author	Year	Summary	Motivation for Not In Depth
An expanded HAZOP-study with fuzzy-AHP (XPA-HAZOP technique): Application in a sour crude-oil processing plant	Panagiotis K. Marhavilas, Michail Filippidis, Georgios K. Koulinas, Dimitrios E. Koulouriotis	2020	Extension of HAZOP through HAZOP+DRMA+FAHP =XPA-HAZOP. The XPA-HAZOP is said to be a functional tool for decision making with regards to ranking of hazards (at least compared to a conventional HAZOP).	Improvement of other risk analysis tools such as HAZOP (where the use of a risk matrix might be a part of the improvement of the HAZOP, but the risk matrix was discussed as a tool itself).
An Innovative Risk Matrix Model for Warehousing Productivity Performance	Hanafiah, R.M., Karim, N.H., Rahman, N.S.F.A., Hamid, S.A., Mohammed, A.M.	2022	The study analyses risk factors that affect warehouse productivity performance. A new risk matrix model is produced by integrating a traditional risk matrix with Borda method and Analytical Hierarchy Process (AHP).	No critique of the risk matrix. Proposed method is not sufficient as the new risk matrix model is only relevant for warehousing productivity. The method suggest a new model instead of the traditional risk matrix.
Comparing quantitative probability of occurrence to a risk matrix approach: A study of chlorine residual data	Lane, K., Gagnon, G.	2022	The study compares two quantitative risk calculations (i.e., probability density function and event trees) with the risk matrix method for water safety planning. In 77% of scenarios investigated, the risk matrix method provided an underestimation or overestimation compared to the probability calculated with actual data. Hence, if data is available, the addition of calculations provides a more accurate picture of risk than the risk matrix.	Comparison of risk matrix with other methods. Hence, the risk matrix method is not developed or improved upon, but instead the study focuses on when to not use it (i.e., when there is much data available).

Title	Author	Year	Summary	Motivation for Not In Depth
From Risk Matrices to Risk Networks in Construction Projects	Abroon Qazi and Irem Dikmen	2019	The study mentions that the industrial practice for managing construction risks is to map them on a risk matrix according to probability and impact. There is critique with regards to this (complex interdependencies are ignored, point estimates are used and aggregation across multiple project objectives is not possible). The study proposes moving away from the risk matrix and instead using a so-called risk network (i.e., new process introduced using a Bayesian Belief Network where risks mapped on a risk matrix corresponding to each project objective are aggregated and modelled as a risk network. Also new risk metrics are proposed to get a more holistic overview of each risk).	The proposed alternative is not relevant to our study as it suggests a path from the risk matrix instead of a development of the method. Although a highlight is made with regards to important shortcomings of risk matrices with the interdependency of different risks.
Fuzzy risk assessment for mechanized underground coal mines in Turkey	Melih Iphar & Ali Kivanc Cukurluoz	2020	The study proposes a fuzzy logic-based safety evaluation method (i.e., a systematic calculus to deal with linguistic information or a so-called mathematical way to represent linguistic vagueness) to deal with the deficiency of the risk matrix with regards to having precise values for likelihood and severity as well as any linguistic ambiguity.	The study concerns handling of input data to make the definitions easier to understand through a fuzzy logic approach. This is more of a model that concerns the input data in the risk matrix. This may be relevant for our study, but then a more detailed study is needed, and this does not go into depth in a sufficient way.
Risk assessment based on novel intuitionistic fuzzy-hybrid-modified TOPSIS approach	Mohammad Yazdi	2018	The intuitionistic fuzzy hybrid TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach is proposed to deal with limitations of a so-called crisp risk	The study presents the improvement of risk matrices by improving the handling of input data. We consider this to be irrelevant for our work, which concerns the model for risk matrices only. Improving input data is a way to improve the result of a risk matrix, but then it is assumed that you continue to use the risk matrix as it is.

Title	Author	Year	Summary	Motivation for Not In Depth
			matrix. Further, it is also proposed to deal with uncertainties of group decision makers using experts' opinions in linguistic terms.	
Risk assessment of information production using extended risk matrix approach	Jaka Sembiring, Fitasari Wiharni	2019	The study covers how to better the risk assessment with regards to information production. An extended risk matrix is proposed.	The study highlights the shortcomings of the traditional risk matrix approach, which is relevant. but the study proposes a development of the risk matrix where a third variable is recoverability. This may be too specific. However, the introduction of a third axis might be relevant as an idea itself.
Risk informed resource allocation policy: safety can save costs	Hans J. Pasman	2000	The study points to advantages of risk assessment and how good risk assessment can reduce costs in the long term. It addresses several different ways of assessing and managing risk, where one of the methods is the risk matrix as a way of visualizing results.	Risk matrix is not discussed as a tool itself and no critique/improvements are given. The study discusses risk assessments in general but not risk matrices in particular (mentions a variety of methods where risk matrix is one of them). Mainly it introduces the risk matrix as a concept. As the study is from 2000 this may be a problem since the science on this field has been developed a lot since then. This may also be the case as to why this article has been written - to point out that risk assessments are important and introduce different risk assessment methods.
Safety Considerations by Synergy of HAZOP/DMRA with Safety Color Maps—Applications on: A Crude-Oil Processing Industry/a Gas Transportation System	Panagiotis K. Marhavilas, Michail Filippidis , Georgios K. Koulinas and Dimitrios E. Koulouriotis	2021	The study covers a proposed synergy of HAZOP, (Decision-Matrix Risk Assessment) DMRA together with colour maps (SCM). This in order to identify critical points at a plant (in this case sour crude oil plant) and visualize the occupational safety and health situation (OSHA). The outcome of the study showcases how parts of a plant can be colour mapped in different ways based on the HAZOP and DMRA.	The study covers how risk matrices can be incorporated with HAZOPs and colour maps to better visualize the risks and where they are located on a plant map (i.e., colouring the nodes). The study does not propose improvements to the risk matrix or critique it.
The integration of HAZOP study with risk-matrix and the analytical-hierarchy	Panagiotis K. Marhavilas, Michail Filippidis, Georgios K. Koulinas,	2019	The study advocates the development of HAZOP, E-HAZOP where DMRA is part of the analysis	Improvement of other risk analysis tools such as HAZOP (where the use of a risk matrix might be a part of the improvement of the HAZOP, but the risk matrix was discussed as a tool itself). The study does not propose improvements to the risk matrix or critique it.

Title	Author	Year	Summary	Motivation for Not In Depth
process for identifying critical control-points and prioritizing risks in industry – A case study	Dimitrios E. Koulouriotis			
The interdiscursive appeal of risk matrices: Collective symbols, flexibility normalism and the interplay of 'risk' and 'uncertainty'	Silvia Jordan, Hermann Mitterhofer,, Lene Jørgensen	2016	The study investigates risk matrices as a tool for risk assessment and visualization. Further, the so-called interdiscursive character of risk matrices (i.e., the fact that complex themes and insights from specialized discourses and disciplines come to permeate 'everyday life') is assessed and it is focused on the fact that the risk matrix can - due the use of their "general symbols" - link very complex themes with everyday life making them possible to understand for the general public.	The study explains in detail, with a scientific basis, problems with the risk matrix, how it is difficult to grasp complex interdependencies through a very simplified visualization. Clearly highlights the pros and cons of the risk matrix but does not give concrete suggestions for improving the method.
A methodology to define risk matrices – Application to inland waterways autonomous ships	Bolbot, V., Theotokatos, G., McCloskey, J., (...), Boulougouris, E., Twomey, B.	2022	The study covers how appropriate selection of risk matrix ratings shall be performed in the water ways autonomous ships industry. The authors point out that there are very few studies that focus on the development of the risk matrix for a completely new sector. Further, individual risk and societal risk is not interconnected to the risk matrix ratings (i.e., intolerable and tolerable regions in the matrix). The article provides a methodology for developing a risk matrix and defining intolerable and tolerable regions in the matrix with the help of calculations for individual and societal risk.	The study covers development of risk matrices for a completely new sector which is outside of the limitations chosen for the thesis.

10.4 Appendix D - Summary of Reference Analysis Literature

Studies selected for further reading based on reference analysis of Group 1 and Group 2 studies.

Title	Author	Year	Summary	Motivation for reading /discarding
Further thoughts on the utility of risk matrices.	Ball, D. J., & Watt, J.	2013	The article examines reliability and utility for ranking hazards through a risk matrix. It is found that rating is subjective based on underlying factors (e.g., worldviews, belief systems etc) seldomly acknowledged. Risk matrices give an untrustworthy picture of risk.	Full article behind paywall
Designing risk matrices to avoid risk ranking reversal errors	Baybutt, P.	2016	Article discusses flaws with risk matrices with regards to application of the tool in the process industry. The most significant flaw is the potential for risk ranking incorrectly. This article describes how the problem can be addressed for risk matrices specifically for process safety.	Full article is behind paywall
A risk matrix for risk managers	National Patient Safety Agency (NPSA)	2008	The article poses a guide to using an already existing risk matrix.	Not relevant. A guide to an already existing matrix. Does not add anything new with regards to guidance for using the matrix.
Risk matrix input data biases	Smith, E. D., Siefert, W. T., & Drain, D	2009	Article reveals evidence of biases with regards to likelihood and consequences - i.e., centring bias, increase in consequence and diagonal bias.	Full article behind paywall.
The risk of using risk matrices	Thomas, P., Bratvold, R., & Bickel, J.	2014	Study looks at the oil and gas industry and the application of risk matrices. It reviews 30 papers and risk management standards and discusses the use of risk matrices for a variety of contexts. Study discusses and illustrates that risk matrices are subjective, and their problems are inherent to the method, hence other methods are better.	No improvement suggestion, just critique of the risk matrix.
The risk matrix: Uncertain results?	Peace, C.	2017	The article discusses the risk matrix critique based on previous studies with regards to poor design and inappropriate use. Conclusion is that risk assessors need better training with regards	Article read but no new input to our study.

Title	Author	Year	Summary	Motivation for reading /discarding
			to designing the matrix and knowledge about inherent unreliability of the tool.	
Some extensions on risk matrix approach	Ni, H.; Chen, A.; Chen, N.	2010	Study discusses defects with risk matrices and presents extensions of the risk matrix as well as demonstrates the superiority of the method compared to others in a case study. The conclusion is that the risk matrix can be constructed based on how the input is related to each other (i.e., multiplying consequence and frequency or adding them or subtracting them)	Full article read. The study proposes constructing the risk matrix based on iso-risk curves given by different calculation methods (multiplication, division, addition etc). This cannot be given as a general recommendation for improving risk matrices in our opinion as it is only a suggestion of how to construct them.
Risk matrix method and its application in the field of technical project risk management	Q. Zhu, et al.	2003	No safe access	No safe access
Implied accuracy and false assumptions.	Pickering, A.; Cowley, S. Risk matrices	2010	Study discusses the use and development of the risk matrix. The study discusses weaknesses with regards to human bias and that the multiplication between consequence and likelihood can give risk reversal errors. The study concludes that a "shift of emphasis from the risk assessment stage to the risk control stage of a hazard management process may lead to better and more timely decision making and better use of resources" (p.18)	Full article read. The study does not really propose an improvement as it points out that "it may" lead to better decision making and risk of resources. Hence this cannot be used to provide a new recommendation.
A practical guide on how to present and visualize the result of risk and vulnerability analyses in a societal safety and security context	Amundrud, O., Aven, T.,	2012.	-	Article not found
Risk matrix as tool for risk assessment in the chemical process industries,	Ruge, B.,	2004.	This study discusses the semi-quantitative risk assessment in the chemical process industries by using a risk matrix. The risk matrix is also demonstrated with regards to use in two examples.	Full article behind paywall. Further, the study is not relevant as it only describes the risk matrix and its use.

Title	Author	Year	Summary	Motivation for reading /discarding
How to design rating schemes of risk matrices: a sequential updating approach	Li J, Bao C, Wu D.	2018	The study suggests an alternative on how to design the rating scheme (number of ratings used in the matrix and how to assign these to different cells) called Sequential Updating Approach (SUA) consisting of three principles - adjusted weak consistency (AWC), consistent internality (CI) and continuous screening (CS) and an algorithm. It is argued that if risk matrices are used for prioritization, they should have higher resolution.	Full article read. The methodology proposed is quite advanced, but a recommendation will be added regarding choosing the SUA approach for defining rating scheme.
Fuzzy risk matrix.	Markowski, A & Mannan, M.	2008	Review of the theory and method that is the fuzzy risk matrix and why it is helpful to make the risk matrix less subjective	The method has already been reported in more recent articles that have reviewed the method and further developed it
Improvement and application of risk matrix.	Yi C, Zheng C, Fu Q.	2013	-	No access
Calibration of risk matrices for process safety.	Baybutt P	2015	Study discusses how risk levels are given by numerical values in quantitative risk matrices for the process industry. It is mentioned that such risk matrices must be calibrated with reference to appropriate numerical risk tolerance criteria, or process safety target levels, to define appropriate risk reduction requirements. This calibration has several pitfalls and these are presented and guidelines are given on how these can be avoided. It is recommended to calibrate the risk matrix with regards to risk acceptance, where the individual or group risk criteria is divided by the estimated amount of hazardous scenarios leading to the same hazard.	Full article read. The calibration process is used as input for one of the provided guidelines as part of the thesis. The study discusses relevant critique and practical application of the risk matrix and suggests a solution.
Comparison of different methods to design risk matrices from the perspective of applicability.	Chunbing B, Dengshen W, Wan J, Li J, Chen J.	2017	As the design of risk matrices has not reached consensus but several methods have been proposed to help with the design - the current study looks at two different methods for designing risk matrices. They are studied based on applicability. One method where iso-contours are	Full article read. Depending on which method is chosen, it may not work if inputs, scaling, or attitudes towards risk are changed.

Title	Author	Year	Summary	Motivation for reading /discarding
			incorporated into the matrix and a method where the matrix is constructed according to Cox's axiom for risk matrices. The two methods are then compared based on three given scenarios for applicability - change of scaling of inputs, change of distribution of inputs and change of attitudes towards risk.	
Guidelines for designing risk matrices	Baybutt, P.	2018	The article discusses the fact that the risk matrix in the process industry is not standardized and that companies often use their own. However, there are some pitfalls which give invalid risk ratings and may lead to risks being unrecognized. The study proposes guidelines for constructing a risk matrix where these pitfalls are addressed.	Full article behind paywall, but it is suspected that its content is similar to the other article by the same author as the same expressions are used.
Review of the strengths and weaknesses of risk matrices.	Elmonstri M	2014	The study gives an overview of the development and use of risk matrices in different fields. The study takes the risk matrix used in the National Health Service (NHS) in England as an example. The study further presents strengths and weaknesses of the risk matrix.	Full article read. No improvements given apart from the fact that organizations should adjust design and size to suit their specific needs, which is already covered as part of group 1 literature.

10.5 Appendix E - Details of Risk Matrices Identified

Risk matrices identified in ORS Archive, Client Standards and provided additional matrices from key personnel at ORS.

#	Industry	Use	Colour	Axis	Legend	Cell size	Form	Corporate / Specific	Type
1	Oil and gas	HAZID-scenarios were classified with the use of the risk matrix. Conclusions regarding overall design are made based on no red scenarios identified.	3 colours, red, yellow, green	Qualitative labels 1-5 for severity and A-E for likelihood.	Legends are provided for description of each category. Description is also qualitative. Risk rating (i.e., red, yellow and green) is explained with regards to measures to be taken for the respective rating.	Uniform	5x5	Corporate	2
2	Pharmaceutical Company	Initially through to be part of PHA and SIL Allocation study. However, due to the poor quality of risk matrix it was never used.	4 colours - green, yellow, orange, red	No axis. Rows describing likelihood, acceptance, severity, and requirements for barriers.	No legends are provided.	Uniform	1x4	Corporate	N/A
3	Oil & Gas	Used as part of HAZOPs where scenarios with worst consequences in the risk matrix are further subject to LOPA. Also used in HAZIDs for risk ranking and potential discussion of/validation of design.	4 colours - purple, red, grey, green	Frequency is expressed as categories 1-6 with qualitative names for each category based on industry (e.g., category 3=unlikely=has occurred in the organization or more than once in the industry), where each category in turn has a frequency interval (e.g., unlikely=0,001-0,01) . Consequences are also categorized A-F, where environment and asset consequences are given quantitatively with intervals (e.g., A=100 MUSD-1BUSD), whereas safety and reputation are given qualitatively (e.g., negative media coverage for more than five months).	No legends, everything is explained as part of the risk matrix.	Uniform	6x6	Corporate	1
4	Chemical industry	Used in HAZOP and LOPA. Scenarios were risk ranked in HAZOP according to risk matrix and scenarios being “orange” were subject to LOPA.	3 colours - green, orange, red	Frequency is expressed as categories A-F (e.g., category C=heard of in the industry), where each category in turn has a frequency interval (e.g., C=0,001-0,01). Consequences are also given in	No legends, all information is given in the matrix.	Uniform	5x6	Corporate	1

#	Industry	Use	Colour	Axis	Legend	Cell size	Form	Corporate / Specific	Type
				categories 1-5 for people, environment and asset respectively. Descriptions of people and asset categories are quantitative (e.g., 4=1-2 fatalities) whereas environment category description is qualitative.					
5	Energy sector	Risk matrix used for risk ranking scenarios in HAZOP. Scenarios rated "yellow" were further taken to LOPA.	4 colours - dark blue, light blue, yellow, red	Frequency is expressed in with three different values for each frequency category (categories 0-5) depending on what the risk matrix will be used for (e.g., F1==Has occurred in the industry if the risk matrix is used for HAZID but 10=0,00001-0,0001 if the risk matrix is used for HAZOP and LOPA). Consequences are expressed in categories C0-C5 where both people, environment, asset and reputation categories are described qualitatively.	No legends. All information is given in the risk matrix.	Slight difference in cell size on the vertical dimension as consequences increase. Unclear if it is for communication or practical reason	6x6	Corporate	4
6	Energy and Petroleum	This risk matrix has been used previously as part of HAZIDs, however it is now explicitly NOT used for HAZIDs anymore. Instead pure quantitative risk ranking is performed due to the company recognizing bias of a team agreeing on a risk ranking.	3 colours - green, yellow and red	Consequences are categorized qualitatively (e.g., moderate, serious, very serious etc). Frequencies are categorized quantitatively (e.g., unlikely=0,01-0,001). The categories are not represented by numbers (e.g., 1-5) or letters (e.g., A-E).	No legends	Uniform	5x5	Corporate	3
7	Energy and Petroleum	Used for operational risk assessment analyses such as HIRAs (Hazard Identification and Risk Assessment).	3 colours, green, yellow and red	Frequencies are categorized 1-6 where each category is split into both quantitative and qualitative grading, as well as provided in 4 different classes - loss of containment frequencies, compliance, production shortfall and people, environment and asset. Consequences	No legends, all information is given in the matrix	Uniform	6x6	Corporate	1

#	Industry	Use	Colour	Axis	Legend	Cell size	Form	Corporate / Specific	Type
				are given in categories of 1-6, where each category is provided for both safety, environmental impact, compliance, reputation etc. Categories are qualitative for all except asset and safety (e.g., 1MUSD or 2-5 fatalities).					
8	Operators of various LNG vessels	Risk matrix used for risk ranking in HAZOP. Unclear whether there will be a LOPA and how the scenarios will be chosen from HAZOP (ongoing project).	Three colours, green, yellow and red	Three consequence categories (1-5) with three types of consequences (safety, environment, asset) described qualitatively for people and environment, but quantitatively for asset. Five frequency categories (A-E) described qualitatively based on industry (e.g., C=Unlikely=Has occurred in industry but rare) and further given frequencies (e.g., unlikely=0,01-0,001).	No legends	Uniform	5x5	Corporate	1
9	Oil & Gas	Used as part of a HAZOP study meant to confirm a proposed design. I.e., no scenarios identified in the HAZOP study were ranked as yellow and hence the design was accepted.	3 colours - green, yellow and red	Frequencies are categorized VL-VH (Very Low-Very High)in 5 categories (VL,L,M,H,VH). Each category is represented by a percentage (e.g., M=10-25%). Consequences are categorized in the same way as likelihood (VL-VH). Legend is provided for describing consequences in terms of asset, schedule, production, safety, environment reputation, legal and long term value impacts. Further, commonly identified HAZOP scenarios are pre-inserted into the risk matrix for comparison (e.g., hydrate plug during start-up is L frequency and H consequence). The consequences are specifically adjusted to the field analysed in the HAZOP study.	Legend is used describing consequences of each category and class (e.g., Low cost = 10 to 100 MNOK)	Uniform	5x4	Site specific	2
10	Oil & Gas	Used for risk ranking	Three colours -	Probability categorized from P1-	Giving two different categories for	Uniform	5x5	Project specific	2

#	Industry	Use	Colour	Axis	Legend	Cell size	Form	Corporate / Specific	Type
		scenarios in HAZID for awareness of risk related to the specific activity being subject to HAZID (lifting activity in relation to light well interventions).	red yellow and green	P5 where each category corresponds to likelihood (e.g., P1=extremely unlikely, P5=almost certain). Consequences categorized from I1-I5 where each category corresponds to impact (e.g., I5=Very high).Legends are given for describing each probability and consequence category further.	frequencies (probability terms paired with description and chance of occurrence, .e.g, P1=extremely unlikely=0-5%=Rarely or never heard of in the industry). Impact or consequence is described qualitatively for safety and environment but quantitatively for asset (i.e., given in three classes)				
11	Oil & Gas	Risk matrix used for risk ranking as part of HAZOP study where an alternative configuration for a new use of a well is studied - i.e., risk ranking used in order to see if the alternative configuration is feasible.	6 colours - dark red, red, pink, orange, yellow and white.	Probability categorized from P0-P4, and consequences are categorized from S1-S4. Each combination of probability and consequence corresponds to a letter being the risk class (e.g., P0:S1=Risk class A). Legends are used for further describing each probability and consequence category as well as letters.	Legends are used to describe different consequence categories as well as their meaning in terms of different classes - environment, health, reputation and asset (e.g., S1 asset = potential for major damage above 1000000 euro). Legends also used for explaining the probability axis (e.g., P1=0,1) and letters	Uniform	5x4	Corporate	2
12	Technology provider for marine and energy sector	Used for risk ranking HAZOP scenarios, where scenarios with certain risk ranking were further subject to LOPA.	4 colours - green, yellow, orange and red	Frequencies described with 5 categories (1-5) and consequences described in 5 categories (1-5). Risk rating of each combination of category of likelihood and consequence is given in terms of a letter (i.e., consequence 1 and likelihood 1 is A). Explanation of letter is given below the matrix (e.g., A=Acceptable, no control measures needed, N= not desirable, control measures should be in place prior to LOPA)	Legends describing 3 consequence categories and frequencies in quantitative (e.g. likelihood category 2 = 100-10000 years equal to unlikely to occur in plant lifetime)	Uniform	5x5	Corporate	2
13	Chemical Industry	Risk matrix used in HAZOP to rank scenarios. Scenarios with intolerable consequences and credible causes may be further subject	3 colours green, yellow, red, and green.	Frequency categorized 1-5 where each category is given qualitatively and quantitatively (e.g. 2=very unlikely=0,0001-0,001). Consequences categorized 1-5	No legend. Another matrix (severity matrix) is provided to use in conjunction with the risk matrix.	Uniform	5x6	Corporate	3

#	Industry	Use	Colour	Axis	Legend	Cell size	Form	Corporate / Specific	Type
		to LOPA.		qualitatively (e.g., 2=major), No legend					
14	Oil and gas operator	Matrix given by ORS and not identified in project - ORS personnel did not know how this matrix was used with regards to HAZOP and LOPA but found it in another archive.	5 colours corresponding from low to very high	Grades axis, consequences 1-6 and frequencies graded a-f	Legend used for describing the gradation of axis and template for the usage of the matrix	Uniform	6x6	Corporate	2
15	Oil and gas	Risk matrix was used partially for risk ranking during HAZOP. However, only consequence severity was assessed, hence a complete risk ranking was not performed.	Four colours: light blue, blue, yellow and red	Four consequence categories, people, assets, community and environment. Likelihood categorized a-f and described qualitatively (e.g. has happened once per year at the location in this organization). Consequences categorized 0-5 and described qualitatively for asset, community, safety and environment classes	No legends	Uniform	6x5	Corporate	1
16	Oil and gas	The use of the risk matrix is for assessing risks from hazard identification analysis (HAZID, HAZOP)	Three colours green, yellow, red	Likelihood categorized A-F where each category is quantitative (B=0,000001-0,0001). Consequences are categorized 1-5 and each category is classified in terms of safety, asset, environment, reputation, security, economy and schedule. All consequence categories are qualitative.	Other tables are provided to be read in conjunction with the risk matrix. Gives a more detailed explanation of the categories. Not a real legend	Uniform	6x5	Corporate	1

10.6 Appendix F - Summary of Interviews

Interviewee no.	Introduction of interviewee (position in organization.)
1	Principal Consultant. Has worked with risk matrices during chairing of PHAs such as HAZOP, HAZIDs etc.
2	Principal consultant. Chemical Engineer. Chairs PHAs such as HAZOPs, LOPAs, HAZIDs etc.
3	Chemical engineer, PHD in chemical engineering, Consultant science 2004 in Oil and Gas Industry - part time process engineer, part time process - transition to safety engineering, risk assessment. Works a lot with QRAs as well as HAZID and HIRA, using risk matrices both quantitatively in QRA and qualitatively.
4	20 years in petrochemical - process engineer and manager. Changed path to process safety and HSE. Worked as a consultant as well as being part of academia (lecturer and PhD). The interviewee founded IPS. Has chaired PHAs where risk matrices have been used. Mainly coarse risk analysis (HAZID) where risk matrix has been used. Has also written IChemE text about risk management covering risk analyses and risk matrices.
5	Principal safety consultant for 10 years, works with process safety. Former process engineer and research scientist. Risk matrix are used in workshops to risk rank. Mainly HAZOP/HAZID and PHAs.
6	Chemical engineer. Consultant and section manager of a safety section. Works with performing risk analyses, mainly HAZOPs and HAZIDs. Focus is on process safety and coarse risk analyses in various projects. Risk matrices used for showcasing results from the analyses.
7	Postgraduate. studies standardization of risk analyses. Former consultant towards industry for approximately 20 years. Risk (fire) engineer. Has used risk matrices as part of PHAs.
8	8 years at the county administration as Seveso inspector, 10 years at the Swedish Civil Contingencies Agency, primarily working with Seveso legislation. Works with educating with regards to Seveso legislation and risk analyses/risk management. Risk matrices are mentioned as part of the education that they provide.
9	Chemical Engineer, Master in Risk management and Safety Engineering. Therefore, has some experience with theoretical parts of risk matrices. Has worked with risk matrices of client in various projects. Has updated a risk matrix at current company. Process Safety Manager today. Part of risk analyses such as HAZOPs, HAZIDs, QRAs etc. Mentions that the risk matrix is most often used as part of visualizing results from a coarse risk analysis (not as an own analysis tool in itself). For more detailed risk analyses, other tools are preferred.
10	Worked in production many years. Production manager in steel industry. Experience from chemical and pulp industry. Mechanical Engineer. Has worked with risks in chemical industries. Risk matrices are used in coarse risk analyses to judge what is acceptable at the plant and not. Been part of coarse risk analyses (HAZOPs, HAZIDs).

Interviewee no.	Are you aware of any limitations with regards to using the risk matrix? (e.g., aggregation is not possible, not only tool for decision making, difficulty with standardization)
1	Yes, aware of several. The big limitation with risk matrices is the fact that it is a qualitative, subjective evaluation. Depends on who is using it unless it is a very clear instruction on how to use the matrix. The use of and results from the risk matrices might be interpreted incorrectly. Important to know why it is used and how. Should be careful in using the risk matrix for the wrong purposes. . Good for categorization and communication. Should not be used to eliminate hazards or say that things are safe. The risk matrix should not be the only tool for decision making but more as a communication tool to visualize which scenarios should get more focus on safety barriers. Many clients are not aware of the fact that the risk matrix is not the only tool for decision making. E.g., mentions that only the fact that yellow scenarios go to LOPA might not be the best way as one should be careful if the scenario is incorrectly defined as green and therefore completely missed. Might be good if it is only severity based and not based on position in the risk matrix (as frequency might have been incorrectly assessed or tweaked).
2	Yes, aware of several. Risk matrices are qualitative constructs. Used to prioritize scenarios from PHAs. Main issue is that users tend to copy and paste risk matrices - no calibration to organization or to business. Aggregation is not possible. Points out that the risk matrix is not used to make decisions, but to know that design is good enough. Part of a larger life cycle for safety and not a tool for decision making. Risk matrix is seen as a larger power tool than it actually is.
3	Yes. It can be very subjective with regards to the result of the risk ranking. Results vary from who makes the assessment. Can be unclear how one concluded - can simply be a snapshot of groups opinions if used in e.g., HAZIDs .
4	Yes, aware of limitations. Risk matrix should be used for getting results from a coarse risk analysis according to the interviewee. Important that the people doing the analysis must have knowledge and integrity, otherwise it will be very subjective and might be subject to different biases.
5	The risk matrix is extremely subjective, there is a possibility to manipulate the results in the matrix. The matrix doesn't highlight uncertainty. Many scenarios have large outcome possibilities which the matrix cannot capture.
6	Aware of some limitations. One scale is oftentimes logarithmic (frequency), but the consequence axis can be more subjective or of another scale (linear). This makes the tool mathematically incorrect or difficult to work with. Also, difficulties assigning values objectively, which means that the tool can be subjective. Mentions the fact that one can manipulate values based on how limitations are made (very detailed scenarios can give low probability and hence false sense of low risk).
7	Yes, aware of several limitations. The results of the risk matrix are reflecting the knowledge of the persons doing the analysis and the outcome is heavily impacted by the quality of the “guesswork” of the participants - i.e., subjectivity. The way the matrix is designed regarding categories on the axis, if it is qualitative, quantitative or semi-quantitative. Uncertainty is not handled - it seems more precise than it is.

8	Yes, aware of a few limitations. Manipulation of the results is possible, to make the risk seem to be less significant than what it actually is. I.e., dividing scenarios into smaller ones which have such low frequency and consequence that is acceptable. The overall system risk cannot be presented in the risk matrix. Only risks for a single scenario can be illustrated.
9	Yes, aware of several limitations. Assigning consequences can be difficult. The categories in the risk matrix may not always suit the actual consequence that has occurred. Also, the total risk picture is lost as only scenario per scenario is assessed. Important to have other tools that captures this.
10	Yes, aware of some. Subjectivity is high when deciding upon likelihood and consequences in a coarse risk analysis setting.

Interviewee no.	**What is your opinion on adding a third or fourth dimension to the risk matrix (e.g., detectability, recoverability, strength of knowledge) apart from consequence and probability? What could that dimension be? Are there any limitations to doing this?**
1	Generally positive to ideas that might provide more depth. However, the user friendliness will decrease which might have negative effects as it is often done in a workshop setting with people who might not be familiar with 3D graphs. Might miss people who cannot understand 3D matrices and their input. Strength of knowledge is a good dimension to include. The more advanced the matrix is made, the less user friendly it will be. More uncertainty is introduced when new variables are added as there is an associated uncertainty to each variable.
2	Risk is normally understood as a function of consequence and probability. Does not like adding more dimensions. This creates a new function which might no longer be defined as risk. Uncertainty is introduced as one may not know the relationship between the new variable with the other two ones. Thinks that lower strength of knowledge means higher probability (of e.g., human error) - hence adding that does not really give anything. Adding a third dimension increases complexity. And people might have difficulty understanding the third axis. Also, there will be problems to make correct risk matrices with regards to implementing the third axis. Also, adding e.g., recoverability requires adding the dimension of time. HAZOP will last a very long time if many dimensions need to be considered. In real life, if you do not know the consequence (i.e., epistemic uncertainty), you write that and add action to HAZOP. Otherwise, you take the most conservative consequence.
3	Can see the idea, but it is practically difficult. Takes a lot of time in 2 dimensions, so adding one more would be even more time consuming. No real point to add a third or fourth variable as the risk ranking is not the most important outcome of the analysis according to the interviewee . Experience that quality of risk ranking is subjective, but if more objectivity could be added it could be of value to have more dimensions. It could be of interest to visually show uncertainty. Understands theoretical idea but does not think it would be practicable with regards to time and how the risk matrix is used in HAZIDs.
4	Thinks that the strength of knowledge is very important to include in some way - maybe with regards to the participants of analysis knowledge. Recoverability can be relevant from an economic point of view. Not sure whether a third dimension should be added in the matrix or handled in another way. Not sure if there are any limitations to adding more dimensions. However, sceptical about adding more dimensions as there is so much uncertainty to start with, by adding another dimension the uncertainty

	increases even more as there is associated uncertainty to the new dimension. The leader of the analysis should be completely independent of the project to get an unbiased risk ranking.
5	This depends on what type of workshop the matrix is used in. For some workshops, it can be valuable to add the dimension. Uncertainty and detectability are the variables the interviewee is most positive to. But again, there is still an element of subjectivity regarding the assessment of the new variable (one person can say that they are very confident when that is not the case).
6	The interviewee is of the opinion that addition of more dimensions is valuable. Has actually seen that some matrices have a third dimension implicitly in the frequency (i.e., frequency is assessed with strength of knowledge in mind). Important to add the dimension correctly so that the other parameters are not affected by the addition of this variable (e.g., if strength of knowledge is implicitly included in another variable, the addition would be incorrect). Unsure whether it would actually work in practice to add dimensions due to the fact that there are many things affecting the risks, but all cannot be captured - hence might not be very valuable to add another dimension. Also, complexity is introduced which reduces user friendliness. The interviewee thinks it is worth trying to introduce it and see how it goes
7	Positive to it in theory, but the interviewee has never seen it in practice. Difficult to visualize in 3D, maybe 2D is better but showcasing uncertainty/strength of knowledge. Strength of knowledge is the most desired variable to visualize the knowledge of the participants in the workshop. The implementation is not the limiting factor, it is the difficulties to see the need for it. Limitations are that it takes longer time in a workshop setting.
8	Positive to visualize uncertainty in the matrix as an idea. According to the interviewee, the uncertainties should be highlighted explicitly. It is difficult to demonstrate uncertainty as it is now, and it is generally lacking when presenting results in the matrix.
9	Sounds interesting to add a third or fourth dimension. However, things it becomes too complex in practice and that results may be unclear. Also, uncertainty is currently assessed by being conservative if the uncertainty is large. Hence, it may not be necessary to add uncertainty dimension. Sometimes, the uncertainty is also described in text and that a conservative approach has been used. Does not really give additional value to add more dimensions according to the interviewee. Increases complexity.
10	Thinks adding a third dimension seems complex. The way this person works with risk matrices, they have difficulties with just the 2 dimensions – adding another requires more education and therefore decreases user friendliness. Seems theoretically reasonable, however. Risk matrix is primarily used for looking at a consequence and then adding safeguards to decrease probability – therefore, adding a third constant axis would not give additional value.

Interviewee no.	What is your opinion on the integration of prediction intervals for uncertainty? Are there any limitations to doing this?
1	Positive to the idea of using prediction intervals. Uncertainty is not illustrated when using just a dot to illustrate a scenario. No preference whether it should be a prediction interval in the form of a line or box. Uncertainty should be visualized as it is currently not captured enough currently in the use of the matrix. For practical use, sometimes the consequence is not known and therefore the risk ranking is not performed. However, it may be much better to actually visualize the uncertainty in the matrix and provide ranking based on that or do something in order to minimize the uncertainty and make a better ranking.
2	In PHAs, failures are considered conservatively, hence variation is not considered as worst credible case scenarios are identified. No need to add it in this context. There is also not enough time practically to consider this in the PHAs where the risk matrix is used to present results. Will take too long to implement this for all scenarios and becomes too complicated, especially if long HAZOPs with many scenarios are performed. Better done for specific scenarios through e.g., QRA and not as a part of improving the risk matrix. When humans are discussing things around the table in HAZOPs, this will take too long to practically implement.
3	Never seen these kinds of intervals before. With a lot of scenarios, you end up with a lot of dots, which makes the matrix crammed and poses a visual impairment. Could be beneficial if used to showcase results in QRAs, but not of value in a workshop setting. Limitations seem to be time-consuming to do in a workshop.
4	Likes the prediction intervals. The risk matrix has a large problem with uncertainty to begin with, showcasing it in this way could be useful for a more accurate representation of results. This is because this improvement gives an expression to the inherent limitation of the matrix - namely the uncertainty. However, this could impose some practical difficulties. In case the uncertainties are very large it will not be useful in practice as there will end up with a visual impairment. In a coarse risk analysis, time could be a limiting factor - however, some sort of estimations with regards to intervals can be made and the use of these prediction intervals can be used. Also, it might be even more difficult to make decisions based on this. Interviewee however likes the prediction intervals a lot. Could also be used for more technical risk analyses such as a QRA. In that case, this would be very useful. Furthermore, intervals can be added to a risk matrix used for management, whereas the matrix used in the workshop can be simpler.
5	Positive to visualizing uncertainty with prediction intervals. This can make it possible to not stay in one cell and actually show the range in which one can be. No additional limitations with adding intervals more than the inherent limitations with the matrix itself (subjective etc). Might provide a basis for sorting scenarios with the addition of prediction intervals. In workshop settings it might save time as it can be easier to come to a compromise when intervals can be used over grids. Limitation can be such that the interval is large, and one can think that it is safe due to this when actually not.
6	Thinks that this way of showcasing aleatory uncertainty is better than for instance with a third axis. Sometimes the uncertainty is unknown and therefore this can impose difficulties. **Proposes more anonymous risk analyses where participants can vote on the risk ranking.** In a workshop setting, people who speak up the loudest are usually the ones making the decision of risk ranking. Furthermore, the sum of opinions usually gives a more correct result according to some experts. However, there is a risk that people who lack knowledge take over the ranking which gives an incorrect result.
7	Positive to the theory but can see challenges in the implementation and don't think that it is comprehensive enough. Decreases user friendliness. May lead to people making estimations without really understanding what they are doing. The strength of the matrix is the intuitive understanding, this removes that intuitive understanding. The strength of the method in the simplicity is lost if it is made too complex. Positive to the voting suggestion to form the intervals. Difficult to implement in practice. Possible limitations that it is time consuming.

8	Positive to using intervals, this can be an alternative to assign a single value. Is of the opinion that this is a good way of showing uncertainty in a matrix. Positive to using the intervals as a representation of the opinion from a group in a workshop. Does not see any practical limitations with regards to adding intervals to the matrix. There might however be a discrepancy between which part of the interval is focused on - e.g., government representatives and the business side since the legislative representatives are more interested in the more conservative values and the business side is less conservative to limit costs.
9	The prediction intervals are already part of the used intervals/categories of the matrix. In case of being in between two categories, the most conservative will be used. Hence, no added value of having prediction intervals in practice. In a HAZID/HAZOP adding prediction intervals for both consequence and frequency could give added value in theory, but this is not worth the time it requires according to the interviewee, combined with the fact that the prediction interval is implicitly built into the risk matrix categories.
10	Prediction intervals would not give additional value in practice, as the worst consequences will be chosen regardless of interval. The interval is implicitly made during discussions, but in reality, the worst consequences is still chosen after all. Might be theoretically reasonable, however.

Interviewee no.	**What is your opinion on showcasing epistemic uncertainty in the risk matrix? How would you do that?**
1	Depends on which type of analyses is performed. For a HAZOP/HAZID it may be too advanced to illustrate uncertainty in this way. It can get too complicated and the one reading the analysis might not be able to interpret the result from it through the now more advanced matrix. For some contexts it might still be relevant. Showcasing uncertainty in a simpler way might be good but in a simpler way (such as an arrow showcasing uncertainty). As long as it is done in a simple and understandable way, it is of value to showcase uncertainty.
2	Practically difficult since people are not aware of what they do not know. Hence, epistemic uncertainty will be difficult to account for in PHAs. By the time a HAZOP is performed, there should not be uncertainty with regards to these parameters. Does hence not think it is of value to show epistemic uncertainty in the risk matrix. Once again, when there is high uncertainty, simply using the most conservative consequence is preferred. This type of illustration might be useful for companies to know the quality of what they are doing. Comparing results between different HAZOPs with regards to epistemic uncertainty illustrated in the risk matrix and seeing which HAZOP teams have less uncertainty during their workshops and why.
3	Have experience of using something like this for advanced QRA, but not good for a workshop setting due to time constraint and user friendliness. Can see a point of using this for the more important (red) scenarios - but not for all scenarios. E.g., only for the 10 worst scenarios.
4	This improvement would give an extra edge to the matrix, but this is also a step towards making the tool too complex. Unsure whether it is actually practicably applicable as well in a workshop setting. Requires a lot of background/base which might not be the case in a coarse risk analysis. Many participants in the workshops might be unsure about how to use this, which poses practical limitations to the use. However, risk ranking can be performed by the safety lead and not all participants have to be involved hence managing the issue with potential misunderstand/not understanding the tool during the workshop. This way of improving the risk matrix introduces a more academic dimension. Generally, likes moving in this direction with regards to improvements, however important to not take it too far as to make the tool too complex and not practicable with regards to time and people using it.
5	Positive in theory but it is difficult to implement in practice. People would not understand it in the workshop and to also come to terms with each other in a workshop with regards to model, data and judgment for both consequences and probabilities. The method is complex but the idea to visualize general uncertainty would be a possible improvement. It would make a coarse analysis unnecessarily complicated and time consuming. Proposes to simply use intervals to capture both aleatory and epistemic uncertainty.

	Can be good with regards to illustrating results in a QRA however.
6	The interviewee also finds this valuable. However, it might be too much work in a workshop setting to make this type of assessment. The interviewee does not consider this too complex as it is a matter of habit. Also, for those not knowing how to interpret this type of matrix, the matrix with the scenarios inserted in itself is still enough - everything else can simply be disregarded by those people which is not possible with a third dimension as the whole matrix is then altered. Adding this type of uncertainty illustration would increase differentiation between yellow scenarios which interviewee considers good.
7	Positive but there are constraints in comprehension and the model becomes very complex. The strength of the risk matrix with simplicity is lost. The simplicity is lost without bringing in too much value. The "red" scenarios are might the most relevant to visualize the uncertainty for, giving a relevant trade-off between time and result. (risk matrix is used to much and the result of the risk matrix is to heavily weighted, the method should be used for a more course analysis and it should be used as a part of a greater analysis)
8	The interviewee is of the opinion that showcasing uncertainty is of gain and that this method is a potentially good way of doing so no matter what kind of uncertainty it is. No suggested implementation issues. It is however difficult to assess uncertainty, it requires a very experienced group or individual to do the assessment. There is a potential conflict of interest between government representatives and the business side since the legislative representatives are more interested in the more conservative values and the business side is less conservative to limit costs.
9	Does not think it adds value to the risk matrix to have this type of illustration of uncertainty. Further, being very uncertain is not preferred, hence being more conservative is preferred so that the uncertainty is decreased. Also, if participants of HAZOP are unsure or cannot judge something with certainty, the HAZOP will simply not be performed. Used statistical values for frequencies are further assumed to be green/yellow. Dealing with uncertainty in this way increases complexity. It is already complex as is in coarse risk analyses – by adding this uncertainty in this detailed way will make the matrix too complex in the coarse risk analysis context.
10	Likes this way of visualizing uncertainty (much more than the 3D risk matrix). Also mentions that if uncertainty is high, it might be reasonable to continue with a more thorough analysis and this can be a way of catching this. Easy to understand. Also thinks it is relevant in the context to showcase uncertainty for both consequences and probabilities.

Interviewee no.	**There are some studies with regards to plain visual improvements of the risk matrix for increasing perception. What is your opinion with regards to changing category labels, increasing cell sizes and removing legends? Are there any limitations to doing this?**
1	Everything that can make the understanding and communication is positive as communication should be the main purpose of the matrix. Positive to the idea of not using legends - the more in one picture, the better. Same thing regarding logarithmization of the grids and naming categories according to difference is size. Psychological effects for better communication are good.
2	Positive to this type of improvement of the matrix. Positive to the visual improvement and visual aids. Especially positive to cell size increase to showcase that e.g., the red grid in the far-right corner is largest and worst.
3	Not sure if this will make a great difference. Is of the opinion that it is positive to use both text and numbers to describe the different categories and not negative to a legend. Not sure the visual improvements would be of value. Does not think this is the main thing with regards to improvements of the risk matrix.
4	Positive to visual improvements, especially with regards to the increased cell size and the use of no legend. Has never used a matrix like this. Unsure whether this is necessary as the interviewee has had a lot of experience with the "standard" risk matrix where that has been practically sufficient as the interviewee understands logarithmic scales very well and the "cell size increases in my head".

	However, the interviewee thinks about whether it can be useful for people who are not used to using the risk matrix even though the interviewee themselves does not really need it. Has not used matrix with legend and does not like the idea of a legend as one has to go back and forth from legend to matrix.
5	Positive to visual aids and can see that it is practically possible to implement. Does not think it matters if legend is used or not. So not sure that this is needed.
6	The interviewee has never seen this type of improvement to the matrix. The interviewee is of the opinion that this adds value to the matrix, that this will make the matrix clearer. Usually legends are not used - everything is oftentimes included in the matrix. Meaning that this suggestion might not be relevant. Also, simple to introduce this type of improvement practically. Limitations may be that some cells become very small in an A4 report format. If many scenarios should be placed in a small grid it can become cluttered. **Proposes that the risks can be visualized with larger dots/letters also. Also proposes that coloring should be done afterwards to decrease bias and the fact that many scenarios are yellow. This would increase objectivity.**
7	Positive to the visual improvements especially the visualization of logarithmic scale through numbering the axis visualizing the factor and they are new to the interviewee. Possible clutter when smaller cells are filled with scenarios. With a large cell, it can be interpreted as it should be "filled" with many dots which might lead to misunderstanding.
8	Positive to information given in the matrix instead of supplied in a separate legend. Positive to increased cell size to visualize the scaling in the matrix and the implementation of these suggestions should be easy to do and the interpretation of the "new matrix" should increase as it becomes more familiar to work with.
9	Positive to visual improvements. Thinks it is a very good idea. Especially positive with regards to name of categories and not using legends. Cell size can become complex if doing it to scale (matrix becomes too large) but can make it larger not to scale.
10	Thinks just adding these visual improvements will not be enough. Wants examples of scenarios and where they are for comparison. However, still thinks the visual improvements are of value – especially with regards to cell size as it makes one think with regards to the categories. Will add value practically.

Interviewee no.	**Would you consider extending the risk matrix axis to decrease centring bias? Are there any limitations to doing this?**
1	Everything that can diminish bias is good. The interviewee confirms that centring bias is present. Furthermore, confirms that the colour affects judgment as a lot of people generally want to grade scenarios yellow and not red. Main problem from experience is that colouring bias is more present than centring bias. **Provides a recommendation of not using any colours during the HAZOP so that the scenario is only judged based on consequence and likelihood. Afterwards, the colouring is disclosed.**
2	Confirms centring bias being present. Unsure about extending the legends to counteract it. People should know how to use the tools correctly and have clear rules for which values are assigned and why instead of "tricking" them by extending the axis. Very clear rules are better to implement than just extending the axis. Humans will find ways of making cells yellow and avoid high risk scenarios, even after the extension of axis. Could be of use for purely qualitative matrices, because quantitative are better managed with clear rules.
3	No experience of centring bias - has seen the opposite - people trying to place scenarios in the green or in the red corner. Is not positive to larger matrices, going from 3x3 to 5x5 or 6x6. Making the process more time consuming when having to discuss where to place scenarios in a larger matrix.
4	Unsure about extending axis. Not sure what to answer. Has experience that most risks are in the middle due to "their nature of not being completely green but also not very severe". Usually "green" risks are also not considered/documented in the analysis and plotted which might increase the experience of centring bias.

	Adding extended axis might lead to more practical work and make the analysis take longer or make the risk matrix more complex than necessary, which is not of use. Simplicity is essential when performing a coarse analysis. If that is lost by adding extended axis the interviewee does not consider it an improvement.
5	This could make the matrix too complicated, and the added resolution isn't needed. Might also add an unrealistic category and that in workshop setting scenarios would be categorized in a way that actually does not exist (just added to counter centre bias). In a workshop setting, the simpler matrix the better. Adding more grids would make it more complicated as time is used to discuss whether it is 6, 7 or 8.
6	Confirms centring bias from real life experiences and also that most scenarios are "naturally " in the middle as red are unusual and green are oftentimes not showcased which might increase the experience of centring bias. Also thinks that scenarios are often yellow and not necessary only in the middle. Extending axis seems reasonable to decrease centring bias. Adding more cells does not increase complexity according to this interviewee. Unsure if this would help a lot as all the other issues with the risk matrix will still remain. **Proposes to not show the matrix during the workshops to counteract biases, instead just asking about consequence and frequency which is afterwards added to a matrix. However, there might be difficulties with "openly" assessing these things without categories. This can be counteracted by asking "does this occur more often than 1 per 100 years" and if "yes" than "more often than 1 in 10 years". The interviewee notes that there may be time limitations.** Often does a sanity check after a scenario has been placed in a grid. Oftentimes the workshop group does a second round after an assessment has been made to make sure it still feels reasonable.
7	Confirms centring bias from practice. It is possible to have an even distribution of cells e.g. 4x4 to make it "impossible" to place scenarios in the middle forcing a decision. Might not be a need for a matrix with an increased number of cells. More positive to an even number of cells than elongating the axis. With more cells, a need for more categories and they might be difficult to define.
8	It is a good suggestion if it creates a more truthful matrix. No practical limitations of extending the matrix.
9	Has not seen centring bias from practice (however uses the risk matrix in such a way that it is built into the HAZOP/HAZID worksheet, hence the colour appears after the assessment has been made – matrix is not seen during risk analysis itself). Does not like extending axes as it increases complexity and time necessary for the analysis.
10	Has seen centring bias from reality in connection to risk matrices where categories are not clear. Does not like extending axes as it is actually not an improvement as people will still just add things in the middle without further consideration. Also unclear about adding categories – which should they be?

Interviewee no.	**Are guidelines provided on the use of risk matrix in case of an event with several classes of consequences (e.g., safety, financial and reputation). Would you consider providing guidelines and are there any limitations to doing it?**
1	Depends on the client. Guidelines are provided for larger companies, but for smaller ones they are not given. No national standards are given for this. Some want to identify scenarios with regards to each consequence and rank each. Some prefer to only look at the worst type of consequence. Ideally, ranking should be performed for all relevant consequence categories, but this would take a lot of time. Provides a recommendation to have a consequence rule- set which means that if safety category is B: Single fatality, it will automatically mean category C (Reputation): Negative media publicity. Positive to more guidelines with regards to handling of scenarios with several classes of consequences.
2	No limitations on adding guidelines per se, actually important to add guidelines. When there are scenarios with different consequences, each scenario is uniquely defined with regards to the consequences according to this interviewee. However, some people only take the worst-case scenario. It is important regardless to have clear guidelines. Otherwise, subjectivity is increased, and people may not know what they are doing when assessing such scenarios.

	If there are no guidelines with regards to the country, companies create guidelines, and these can vary. Some countries say that you have to define both safety and environment. Also, part of the guidelines should be to consider when you are unsure - to e.g., use conservative values. Some companies do not have guidelines at all. Providing guidelines on how to handle scenarios with several consequence classes is a good improvement of the matrix.
3	Depending on time and client - different consequences are assessed. Guidelines could be of use and valuable. Safety priority. **Proposing a recommendation to have a rule-set could be good for the risk matrix with regards to guidelines in case of events with several classes. Rule set - safety 4=reputation 2. This for the qualitative use of the risk matrix.**
4	Points out that guidelines may be very important, especially if people using the matrix are unaware of the characteristics of the tool. Interviewee has always provided guidelines from IChemE to participants before chairing a coarse risk analysis. Especially mentioning what the different consequence dimensions mean. Guidelines should always be provided. Before the analysis begins, guidelines should be stated so that people know how to manage scenarios with different dimensions of consequences. Especially as the consequences with regards to asset and environment are more difficult to assess (e.g., should asset be with regards to what it costs to build up the damaged equipment again or what the cost for standstill in production is etc.). Important to have guidelines here so there is clarity on what is assessed. Sees no limitations to providing guidelines.
5	Guidelines should be provided as long as possible, however there may be scenarios which don't fit the provided guidelines. Mentions that there needs to be a set of rules to handle such scenarios. Consequence rule sets are provided by some clients. The introduction of rulesets also makes matrices more specific for each plant (one plant may have a stillstand cost of x EUR/hr as a consequence rule set from severe asset damage). Especially as the consequences with regards to asset and environment are more difficult to assess (e.g., should asset be with regards to what it costs to build up the damaged equipment again or what the cost for standstill in production is etc.) (yes, they mentioned the exact same thing). Further limitations are that someone has to provide the guidelines, which is time consuming.
6	Usually, guidelines are given for how to assess scenarios with several consequence dimensions if the client requests so. Worst consequence dimension is oftentimes showcased only, and this gives the risk ranking. But sometimes, clients request to only look at one dimension - when no guidelines are provided, the worst consequence dimension is assessed only. Sometimes all dimensions are given. There is an agreement with the client with regards to how to assess these types of scenarios - so maybe not guidelines per se, but rather an agreement between client and company.
7	The interviewee is expecting that guidelines are provided but aware that this is not always done in reality. The interviewee is of the opinion that guidelines should *always* be provided to make the boundaries of the analysis be set and the way decisions are made should be defined. With the purpose to make comparisons of different analyses possible. The need for guidelines is very large in practice.
8	Not aware of any guidelines, positive to the suggestion to be more consequent in issuing guidelines. The guidelines have to be well-founded to be of use and there has to be flexibility between the usage of said guidelines since all facilities are different. However, there might be problems with having too rigid guidelines as they might become irrelevant for a specific plant or that another method is more relevant for that specific case.
9	Guidelines are provided as part of the company where the interviewee works – three specified categories have to be assessed separately. Considers it very important to have guidelines as there may be some potential pitfalls otherwise.
10	Consequences are assessed for safety, reputation, and environment always. This is clear in the company. However, smaller analyses might not consider some dimensions. Thinks it is important to have guidelines for handling scenarios with different consequence dimensions.

Interviewee no.	How are risks with the same score/in the same cell prioritized? Are there any guidelines for prioritization? Would you consider providing guidelines and are there any limitations to doing that?
1	Is not aware of any rule on how to prioritize risks in the same cell. In practice, it does not matter if two scenarios have the same score/are in the same cell. It only means that they will be handled with the same procedures. No need to provide guidelines for how to differentiate between scenarios in the same cell as they will be followed up individually either way.
2	No prioritization is made. No guidelines for prioritization of risks in the same cell. If they have the same score with regards to asset but not safety, then safety one has higher priority. This is not a guideline but simply how this person interviewed is doing it. Adding guidelines would be an improvement with regards to this issue. However, with regards to handling the scenario, they both need to be handled. Same risk ranking means they have the same priority and will be handled with the same procedures - no need to prioritize further, i.e., no need to consider guidelines for doing that.
3	Depends on the situation. For one of them it may be easier to improve the situation, then you will take action in the analysis (HAZID). In the other scenario, it is just the residual risk. Risk matrix not used to prioritize those in the same cells. They have the same prioritization so there is no need to provide guidelines. No concrete guidelines, but in practice consequence means more than likelihood. Personnel safety means more than environment, which means more than assets.
4	The interviewee does not know how to answer this. In reality management handles the result of the analysis, and management will make the decision on how things are prioritized. Oftentimes no guidelines are given in practice. Unsure whether guidelines should be part of the risk analysis or rather management instead. Thinks that it will be too much management to handle for the people in the workshop, and extensive prioritization schemes may result in things not being followed up due to too much complexity. Further, the participants are not responsible for the prioritization.
5	Scenarios should be treated as the position in the matrix stipulates and might not need to rank between equally ranked scenarios. Could be positive to rank regarding uncertainty/strength of knowledge. Potential differentiation is provided if scenarios in the same cell are handled differently (e.g., one goes to LOPA, whereas one is mitigated by adding a corrosion inhibitor).
6	No differentiation between risks in the same cell with regards to how they are prioritized. Differentiation is only made if they are of different consequence dimensions - then one scenario of one dimension might be prioritized over another. This can be per client request. In case more information is added like a third axis - it can make the prioritization easier to perform. If no guidelines are given, the issue is discussed with the client and agreed upon. Hence no need for guidelines.
7	No differentiation between risks in the same cell with regards to how they are prioritized. Scenarios in the same cell should be prioritized equally. Simplicity and cost effectiveness is oftentimes the basis for prioritization in reality. Don't think that strength of knowledge adds value for prioritization. Is of the opinion that guidelines should always be provided for how to handle something like this.
8	Scenarios in the same cell should be treated equally. No present guidelines in how to handle scenarios in the same cell. Might have to be a discussion between legislator/consultant and business practitioner if there is a need for a differentiation between scenarios in the same cell and if so how to handle the scenarios. Here the notion of uncertainty as a basis for how to prioritize the scenarios might be relevant.
9	Prioritization is made based on consequence type (e.g., asset is not as prioritized as safety/environment). Also prioritized based on how easy it is to do something about the scenario. No guidelines available for how this prioritization is made. Thinks it is important to add guidelines with regards to how scenarios in same cell should be prioritized as it is otherwise made in one way or another (and they are often not prioritized differently). One guideline can therefore be that risks in the same cell should be prioritized in the same way.
10	No difference is made with regards to scenarios in the same cell. However, in practice there might be different prioritizations based on what is easier to handle. Thinks that there is a value to create guidelines for this as for instance it might be relevant to differentiate scenarios when one is more unsure than the

	other, and the fact that it is done in practice already even if the intention might be to handle those scenarios in the same way. Important to prioritize uniformly and therefore guidelines are important.

Interviewee no.	When using the risk matrix, which mapping is done first, and which consequences are usually assessed?
1	When used in HAZOP/HAZID, it is easier to value consequence first as it is directly related to the scenario identified. For likelihood, data is sometimes used to assess. Severity is assessed first and then likelihood. Which consequence is assessed is given by guidelines per company. Severity is oftentimes worst credible (without safeguards) in the sectors where the interviewee works, whereas likelihood is given with safeguards in mind. If guidelines are provided, it is clear how the consequence is assessed. For smaller companies that may not be the case that guidelines are provided on which to map first and how to assess consequences. Mentions that it is important to note why the matrix is used - if it is to see the full hazard potential, it should be without safeguards and worst credible consequences. If it is to see that design is robust - it should be with safeguards.
2	Risk matrices are not used in this way by this person. Always looks at the worst credible consequence. For probability, rules are used - pump stopping always has one frequency, valve failing always one etc. Can also use both the worst consequence and most likely consequence. Worst consequences are not considered if they are not credible (design does not allow for it). Uses frequency for the initiating event (and safeguards) and not for the whole scenario with consequence (i.e., conditional modifiers) - so it does not matter that the frequency is assessed first.
3	Prefer to do the consequence first, since it is most relevant for the study in order to actually discuss the frequency of the specific scenario. Normally the worst credible consequence is assigned. Consequence mapping is done first, then frequency for the scenario leading to that consequence. If doing the other way around, there is no agreement on what you are talking about when frequency is assigned. Frequency is with regards to the whole scenario (both a blocked discharge, rupture, explosion and ignition killing 2-5 people).
4	Starts with consequences and then frequency is assigned in a HAZID. Frequency is based on the consequence assigned. The interviewee looks at the most likely consequence even if the worst case is sometimes mentioned. Things that it is important to capture the most likely consequence and not make an analysis that is not representative of reality.
5	Depending on rules set by the operator who owns the risk matrix. Otherwise, and oftentimes the consequence is mapped first. Frequency is based on that specific consequence. Worst credible is mapped since the matrix is oftentimes used in a coarse analysis where the “raw” risk (without safeguards) is what is interesting in this type of analysis.
6	The consequence is mapped first in the and frequency is then based on the full event. Two frequencies are assessed - with safeguards and without. Consequence is the most likely consequence, but this is in agreement with the client. Unclear which consequence is assessed (most likely worst case). Being clearer on which consequence is assessed can be an improvement according to this interviewee.
7	Frequency is as far as the interviewee knows mapped first. Frequency for the initiating event and not the consequence as a whole. The consequence is then added for the frequency and most likely consequence is used. This should be stipulated before the analysis what to map first and which consequence is mapped. Important to state this beforehand, but it is not always done, hence guidelines are necessary. Is of the opinion that mapping risk and raw risk is irrelevant and unnecessary as it brings nothing to the table since the safeguards are actually in place.

8	The interviewee doesn't make risk analyses and cannot answer how the assessment is made and which dimension is assessed first. The interviewee is of the opinion that both worst case and most probable consequence is of interest. However, the interviewee prefers to see the worst-case scenario for their specific position/job.
9	Depends on analysis type. In coarse risk analyses, consequences are assessed before final frequency. However, a frequency is also chosen for initial event, then consequence is assessed and then the frequency is assessed again considering barriers. Worst credible consequence is chosen. However, if there are good barriers lowering the worst credible risk but there is no barrier present for a lower consequence, then the lower consequence is assessed. Clear in guidelines which consequence is assessed and how.
10	Unclear which mapping is assessed first. No uniformity here. Always worst credible consequence is assessed. No guideline for this, but it is clear. Frequency is assessed based on the event leading to the consequence (e.g., explosion after a runaway reaction). Frequency is also adjusted based on safeguards/manning etc.

Interviewee no.	Have you used various risk matrices or only one corporate one? What is your experience with using many different risk matrices? What is the motivation behind the differentiation?
1	Various types of matrices used for different industries. Some companies have very clear philosophies as to why they do the risk ranking (e.g., follow-up of scenarios). Others are not clear as to why they use the matrix. Most often it is **not** clear as to why a specific matrix is used.
2	Has used various matrices. Matrices vary from client to client. Sometimes there are many risk matrices for one client, however, never site specific but more consequences are defined (matrix with safety consequences, matrix with asset consequences etc.). Reason behind differentiation is usually calibration, however, sometimes matrices are just copy pasted. Calibrated matrices are seen when knowledge exists about what is performed. This is because different scales are relevant for different types of analyses (health and safety and process safety - scales are different).
3	Have used various risk matrices, even from different companies. Companies change and update matrices over time. Some are better than others. Usually, it is not that difficult to use different matrices due to experience. Some clients make the process more difficult than what it has to be. Differentiation has been due to trends (3x3 was a trend, then 5x5 etc.). Example of how a new matrix is motivated: New HSE manager that might be more into the environment and has to report spills of certain sizes, then the spill sizes are involved in the matrix (calibrated based on it or having axis describing it). Thinks that the matrix should be based on the need of the client/project
4	Has seen corporate risk matrices, where the corporate is valid for all sites of the company. For smaller companies, “standard” risk matrix is used. Considers that both variants work equally on the premise that the risk matrix is designed properly. Also mentions that trends can be part of creating the matrix from the HSE side. The interviewee considers it to be better to use the same matrix in a company, so everyone is familiar with the matrix. Mentions that it can be good to use a calibrated matrix depending on the context. However, the interviewee is of the opinion that it is better to have one matrix for the company and put “N/A” if it is not relevant for the specific context.
5	Seen many different corporate matrices, but they are often very similar. The dimensions of the axis differ

	based on the company standards. Has not seen different matrices used for the same plant. The different matrices are easy to use if they are fit for purpose by the provider of the matrix. The dimensions of the axis should be appropriate. Matrices are calibrated to the company's risk acceptance criteria. Matrices could be site or company specific. Important to know what the categories actually mean (explaining them in detail). Differentiation is provided depending on company, geographic location, and type of hazards/asset.
6	Different matrices have been seen based on type of assessment. The interviewee mentions that irrelevant risk matrices are used (e.g., workplace environment for a process safety assessment) - this means that some categories are not relevant or do not exist to the nature of that matrix i.e., is irrelevant to the context. No motivation for the use of certain risk matrices.
7	Seen many different matrices and is of the opinion that the matrix used should be fit for purpose and have seen that this is not done in reality. The use of one universal matrix in a corporation has been experienced and it is not ideal. Corporate decisions for the use of a standardized matrix is an easy way out and motivated arbitrarily. Industries that may have work in a specified field motivates the usage of a standardized matrix due to the nature of the activity. This is a very simplified way of thinking. Has seen matrices be “copy-pasted” between different industries where they become irrelevant.
8	The interviewee has seen the “classical risk matrix” but the categories can differ in some cases to be specific for the plant. Does not know how they are designed and what is the background for the matrix categories.
9	Has used various risk matrices – also within one company. Has seen that risk matrices have sometimes been created by a third party, and in that case, it may not be very motivated with regards to what the company assesses to be accepted risk/not accepted risk. Thinks there is practical need to motivate the risk matrix in reality (however motivation can simply be that the company has agreed on this) and it is very important that the risk matrix is line with the values of the company and that this matrix is used all over the company.
10	Has used many different risk matrices in many different companies. Does not know motivation behind them or why they are different. Important that the risk acceptance level based on the decision makers/the company. Cannot answer this question.

Interviewee no.	**Do you think it would be practicable and valuable to change qualitative labels to quantitative? (e.g., through fuzzy-logic)**
1	Most often, matrices are not purely qualitative. Only having qualitative descriptions will make it very subjective and is not good with regards to consistency and providing value to the identified risk. Quantitative labels should be used as it will otherwise become a very subjective assessment. However, there are also very good qualitative descriptions which can handle the subjectivity of qualitative axis by providing detailed descriptions. Fuzzy logic was not discussed further. An alternative to a statistical transformation of the axis of a matrix is to have detailed descriptions into categories for easier categorization.
2	Familiar with fuzzy logic. Not really important to use fuzzy logic itself. This method is simply trying to academize things that people already know. Not practically applicable to use fuzzy logic, and difficult to program into a practical worksheet. However, generally positive to changing axis to quantitative instead of qualitative ones. The company can decide on limits and quantify in that way (e.g., 1-5 fatalities is considered a major consequence). Positive to removing people’s own interpretations and making axis quantitative (maybe even on a country level).
3	Prefer qualitative axis, mostly based on convenience due to experience and that more people in workshops relate better to qualitative descriptions. A good stomach feeling about a risk is important.
4	The interviewee considers it crucial to have at least intervals on the categories. Does not want to have

	purely qualitative matrices as it is then left to each person to interpret what e.g., “major” means. Positive to methods such as fuzzy logic to give quantitative values or at least better qualitative descriptions. Calibration can be performed for each client to identify what a qualitative category means.
5	If it is done it should be done in a way to reflect the company's risk acceptance and not as a part of any analysis. Everything cannot be quantified. Other ways a good qualitative description is better than converting to quantitative. The key thing should be that the axes are described thoroughly.
6	Interviewee considers quantification positive or that the qualitative axes are described in detail.
7	It is difficult to quantify in reality, to define the qualitative descriptions in greater detail is the way to go and possible to do in practice. This is relevant for the frequency categories, use descriptions (has happened in the industry etc.) this is easier to comprehend than numbers. The interviewee refers to detailed qualitative categories as quantitative can give the impression of something being more certain than it is and is difficult to relate to in a workshop.
8	The interviewee is positive to the introduction of the quantitative axis but is in even more favour of a more descriptive qualitative axis as it can be easier to interpret. Otherwise, there might be a large focus on numbers which can be difficult to interpret.
9	Does not think it is a good idea to transform axes to quantitative but may be subject to change with regards to this opinion. Thinks it is enough to have detailed qualitative descriptions – also it may be easier for attendees of a coarse risk analysis to relate to qualitative descriptions. Using numbers can lead to large errors in reality compared to qualitative descriptions. For instance, severe injury may be identified easily with a qualitative description, but a number representing it might be assigned incorrectly the conversion to this number is not understood correctly.
10	Prefers quantitative axes up to numbers in the range of 10^-3-10^3, after that it is difficult to understand numbers according to this interviewee – hence clear qualitative descriptions such as “has never occurred in the industry” is better for very large/small values.

Interviewee no.	**If you use the risk matrix in a PHA, is the matrix calibrated with regards to expected number of scenarios leading to the same hazard? Do you think it would be practicable and valuable to calibrate the risk matrix?**
1	Unsure whether or not the matrix is calibrated. The interview guesses that most risk matrices are **not** calibrated. Calibration seems difficult without doing a deep analysis on how many scenarios there will be. When calibrating, uncertainty is introduced even more which might be negative. Generally reluctant to the fact that summation of scenarios should be done (i.e., calibration based on the number of scenarios should not be performed). Thinks that the risk matrix should be used only per scenario and not with regards to the sum of scenarios and what the acceptance would be based on the sum of scenarios. If the calibration method is fairly simple, it can however be beneficial. Interviewee as seen in reality that discussions exist about the sum of risk so this might be beneficial. Difficult to calibrate beforehand, better to use QRA in that sense.
2	Using the risk matrix in HAZOP is not relevant with regards to this. HAZOP should only look at one scenario at a time. Would also be too difficult to calibrate and use for a risk matrix, even though it might be theoretically correct. Difficult to know how many scenarios are expected beforehand, hence not practically applicable. Might also not be valuable, as one in 1 000 00 years or 20 in 1 000 00 years may not really yield a difference in rating as the change is very small due to the low frequencies.
3	Has not seen the discussion with regards to risk matrices, but only to LOPA. More calibration is not needed, in most cases not relevant. Relevant that company calibrates risk matrix with regards to type of plant etc. but more on a higher level (fish farms are different than oil and gas) and not per scenarios. Says the purpose is to look at one scenario at a time and not aggregate them. Scenarios should be assessed one on one.

4	Unsure whether the matrix should be calibrated or rather just rely on the fact that one can view that several scenarios are given with the same hazard when plotted in the matrix. Based on seeing that a lot of scenarios are in the same cell, the calibration might not be necessary as one already sees that the tolerable frequency assigned can be questionable. The interviewee considers it to be too complex to do this for a matrix. Uncertainty introduced with regards to the number of scenarios and unnecessary as this phenomenon is seen once results are plotted in the matrix regardless.
5	Matrices might be implicitly calibrated over time based on experience with regards to acceptance criteria, but not explicitly calibrated. Quite sure it is not explicitly calibrated. Would be better if it would be explicitly calibrated to begin with. It is valuable but unsure if it is possible to do in practice. Interviewee is positive towards calibration and looking at a sum of scenarios if that is of interest - even if only one scenario is studied at a time. Not sure if it is possible to actually do the calibration. Difficult to know how many scenarios to divide by. Might have to go back and recalibrate time after time or after the workshop. Depends also how the risk accepted is assessed (for one single scenario or for the total scenarios).
6	Thinks that calibration is missing generally. Sum of scenarios should be considered when assessing risk, as the sum is actually what is important - risk on the system level. However, each scenario should be handled individually. The interviewee considers that assessment should be made per scenario (uncalibrated risk), but afterwards summation can be done to assess whether it is acceptable or not.
7	Doesn't expect that matrices are calibrated, emphasizes on the guesswork in the way matrices are used in analysis. This would add further uncertainties and numbers give a false feeling of certainty. Even more uncertainty is introduced when doing this and this uncertainty is not captured with this type of calibration.
8	Is not aware of this. Has not used the risk matrix in PHA.
9	Risk matrix has been calibrated way back based on presumed number of hazardous scenarios. So, this is the foundation of the matrix. Not calibrated per analysis. Does not think it is reasonable to calibrate it for every analysis. However, important that the risk matrix is calibrated with regards to its purpose. On a global level, it is not possible to calibrate as one will have to re-calibrate if the plant expands etc. Risk matrix should be done based on scenario per scenario, whereas other tools should be used to assess systemic risk.
10	Has not seen this type of calibration. It increases complexity. Feels like it can be of value as the interviewee thinks that showcasing the total is good.

Interviewee no.	**Have you ever been a part of creating a new risk matrix? (Decision maker attitude, SUA and Continuous Probability/Consequence diagram)**
1	Yes. The background to the design has been earlier experience and site/industry specific info. For land-based industries, only land-based consequences are applied (e.g., not talking about damage to fishes). Colouring has been done based on “classic thought” and industry specific information. Yellow in the middle between green and red in a diagonal. Client/decision maker has had input to some degree with regards to reasonable categories but not so much with regards to risk acceptance as this was based on industry practice. Gridding should be performed as simply as possible with as few grids as possible - 3x3 matrix. If a more sophisticated review is done, a 5x5 matrix is used. More than that is not necessary as it makes the matrix more complicated to use and reduces user friendliness, therefore SUA or continuous consequence-probability diagram might not be the best approach as it increases complexity. The resolution of the matrix should be chosen based on the need on a case-by-case basis, as a high-resolution matrix may be too complex for its purpose. In a workshop setting, it is more reasonable to have larger categories and fewer grids.
2	Yes.

	Arbitrarily decided regarding how gridding is performed. Calibration point is found with regards to risk acceptance. Sometimes given from the country standard. Below the calibration point in a straight line is coloured accordingly. Risk appetite can be given by the client, as well as very high consequences always being yellow in order to take them to LOPA. Generally, people just copy and paste matrices which is not ideal.
3	Not completely but have been consulting in the setup of either updating of matrices or the creations of new. Usually basing new matrices on existing ones, but then adding characteristics relevant for the use or field where the new matrix is to be used. Also, know that one can do test runs for the matrix where scenarios are identified, and you see if they actually correspond to what risk is expected for that type of scenario. Reality check is important. Never considered continuous diagrams, could be of use in QRA and more technical analysis. Think that a continuous diagram is good for QRA as you then can say exactly where you are instead of throwing the precision away by having a gridded risk matrix. However, adding intervals is not practicable because usually the uncertainty is not known in that detail (Monte Carlo simulations or similar not performed).
4	Yes. Has created the standard matrix used in a handbook at IChemE. Used matrices that were already given and copied the design. Adjustments were made together with industry experts with regards to acceptance criteria and categories. CCPS was used as input. Does not remember precisely how the risk matrix was created. 5x5 matrix was the minimum at the time and this was used. Positive to using a continuous probability-consequence diagram, however the matrix should be anchored with the operators and those working at the facility. Otherwise, they can become lost in more complex matrices, and that would negatively affect the judgements during workshops. Interviewee has seen from practice that simpler matrices are better with regards to letting operators assess risks. Would rather have a too simple matrix, than a too complex one so that people affected by the analysis can interpret it correctly, as these people are the ones giving the input probability and consequences based on their experience of the plant and “real life”.
5	No. would not consider a continuous probability consequence diagram. Prefers a gridded matrix with uncertainty intervals. Continuous safety category not possible since you are either dead or not for instance. Very important that the risk matrix reflects the risk attitudes of the decision makers.
6	Time was not sufficient for answering this question.
7	Yes, arbitrary choice of axis, number of cells etc. The interviewee has created matrices with continuous scales and is of the opinion that continuous scales is an improvement compared to a gridded matrix. It is a trade-off between making decisions and uncertainty. Has done a bit of “copy-paste” of risk matrices with some adjustments. Prefers continuous diagrams from a theoretical point. Difficulty to have it in practice as it is difficult to define exact value or interval in a continuous diagram - might be very large intervals in a continuous diagram. Uncertainties are better illustrated in a continuous PCD.
8	No. not aware of how matrices are created. Is not sure if continuous diagrams, this could however make the matrix too complex. As the simplicity is a good feature of the risk matrix, having a continuous diagram might remove this feature. May also differ too much from the classical matrix which the interviewee is experienced with and hence becomes too complex.
9	Risk matrix was initially thought to be based on literature study, but in the end, experience was used. Looked at other companies. Also, studied how results from previous risk matrices had come out. Adjusted based on e.g., very many scenarios red based on asset in the old risk matrix but safety and environment is more valued, hence it was calibrated down with regards to this dimension so that it was not flagged as red so often when the company cares more about other scenarios. Acceptance levels were set by the higher authorities in the company – but based on best industry practice.

	Having a continuous probability consequence diagram is considered too complex and time consuming to use in reality. Important that acceptance levels are based on based industry practice and that the bosses etc. agree with this. Rather have the acceptance levels based on best industry practice rather than what decision makers think.
10	No, has not been part of creating a risk matrix. Does not know how a risk matrix has been designed or how acceptance levels are decided upon. Does not consider continuous PCDS as complexity is increased and it will take a lot more time in a coarse risk analysis.

Interviewee no.	What is your relation to the risk matrix? (e.g., potential critique, how the person uses it, like/dislike)
1	Risk matrix does not give value if there is no plan as to why it is used - this very often the case. In that case, more time should be spent on identifying input such scenarios and design. Risk matrices are very valuable from a **communication** purpose to illustrate what should be prioritized and illustrate results. It is important to be careful in using risk matrices for justifying removing safety barriers.
2	Likes the risk matrix. Risk matrices are considered one part of the risk management cycle for this interviewee. Risk matrix is the first approach, then LOPA, then QRA. Risk matrices give you an idea of where you are in an early stage by illustrating results there. Makes it easy to see which things should be taken forward and which should not be regarded. Widely used because it is a good **and** simple tool according to the interviewee. Results are good enough for the time and effort put into it. Dislikes usage of risk matrix as a way of calculating the risk. Likes risk matrices if they are used in the right context. Interviewee thinks that many use the risk matrix for more complex things than they are intended for. Points out that the risk matrix is not used to make decisions, but to know that design is good enough. If not, LOPA is done. People using the matrix should be improved, not the matrix itself.
3	Don't like to do risk ranking in a qualitative setting. The results are too subjective. In favour of more technical types of risk ranking with a more technical basis for ranking. Tries to use the risk matrix as little as possible in a qualitative analysis. Likes the matrix as a tool for visualization for quantitative assessments as it gives a good illustration compared to just a QRA with expected loss of life etc. A rule set for using the matrix is needed, to have a more comparable result and consistent results - however this needs some details and can be time consuming (e.g., how many people can a jet kill if release is 10 kg/s, what is ignition probability for different sizes of releases) instead of just using stomach feeling. Also proposes to do risk ranking after the workshop. Only professionals should use it with the aim of getting a better and more consistent result.
4	The interviewee considers the risk matrix a very good tool with regards to interpreting and visualizing results from an analysis. Most people can understand the tool which is positive. Important that the risk matrix is not too complex as its core (namely the simplicity) is then lost. However, the interviewee thinks that matrices can be made more complicated for other purposes. What has been a problem with the risk matrix for the interviewee has been what asset assessment means - cost of re-investment after the accident of standstill time. Therefore, improvements with regards to this (guidelines) are very important. **Proposes that maybe one matrix should be given to management/decision makers and one for the analysis itself in order to make the analysis effective (having the workshop participants understand it).**
5	A risk matrix is a good tool to present the result/group scenarios with regards to severity, but it should not be regarded as a very specific result but a result of a course analysis and a grouping of the results. Can easily give the impression of being more detailed than it actually is. Not sure whether probability grouping actually gives value in a HAZOP as consequence is mainly what is studied.

	The matrix needs a consequent rule set. More information should be provided to the matrix (what its purpose is, limitations, how it is used etc) and rule set is the best improvements according to this interviewee. Sometimes matrices are chosen arbitrarily (copied from other irrelevant industries). Sometimes also one matrix is used for several plants even though they have vastly different hazards. If the matrix is used actively for finding which hazards should be worked further with, then it is important to make the matrix more complex and correct. But if the matrix is simply used for planning, a coarser matrix can be used.
6	Time was not sufficient for answering this question.
7	If correctly used, a very powerful tool. It is a great tool to visualize risk, but it is to great extent used in the wrong way. Valuable for screening of risks and sorting. The reason for using the matrix should be defined. The analysis should be done by competent people.
8	The matrix is easy to comprehend and makes it easy to showcase risks. The interviewee thinks that the matrix is a good tool for visualization of results. Especially as it can be understood by everyone - the simplicity is a very good feature.
9	Is a big fan of the risk matrix overall. Thinks the results from it is in line with what the attendees of the risk analysis and the company “feels”. Also, it gives good foundation for improving the safety. Works well in practice and is in line with standards. Much is given from the time and effort put into it. Risk matrix is also used in context of more detailed analyses (e.g., fault tree) and exact values are given in the matrix.
10	Considers it a good tool, and a good way of visualizing whether more should be done in the production or whether something is inacceptable.

10.7 Appendix G - Experience after interview

According to Bryman (2018), the following was noted down after the interviews:

- How the interviews went (the state of the interviewee e.g., nervousness, collaboration).
- Where the interview was conducted.
- Other experience of the interview (if there were any new ideas provided).
- Environment (calm environment, background noise etc).

Interviewee no.	How the interview went	Interview location	Environment	Other experience
1	Good, all questions asked in the correct time window. Good environment, calm interview, no nervousness from any party and good collaboration. Answers provided for each question and very specific answers as well.	MS Teams	Calm environment at home and in the office. No background noises etc.	Interview went better than expected with regards to time and provided answers. However, a shorter follow-up was made the following day to clarify a couple of the answers and ask a couple of follow-up questions.
2	Good, but took much more time than set aside. Quite difficult to get concrete answers from the interviewee. Good environment, calm interview, no nervousness. However, tiredness got to us in the end.	MS Teams	Calm environment at home and in the office. No background noises etc.	Interview was longer than expected and some difficulty with getting concrete answers and misinterpreting questions. Nevertheless, the interviewee gave elaborate answers to the questions and provided many opinions and arguments which are of value.
3	Good, on time and very specific answers with good motivation behind them. Answers provided for each question and very specific answers as well. Good environment, calm interview, no nervousness.	MS Teams	Calm environment at home and in the office. No background noises etc.	Interview went better than expected with regards to time and provided answers. Interesting to get a little bit different angle on it as this person has a bit different experience than 1st and 2nd interviewee.
4	Good, but took much more time than set aside. Interviewee found the questions a bit complex and mostly answered “I don’t	MS Teams	Calm environment at home and in the office. No background noises etc.	Different contexts provided for the use of the matrix and country, which gave some new insights.

Interviewee no.	How the interview went	Interview location	Environment	Other experience
	know. I guess it is reasonable" to begin with. But once the discussion went on, actual answers and opinions were presented. Good environment, calm interview, no nervousness.			
5	Good, and took less time than set aside. Good and concrete/direct answers provided. Good environment, calm interview, no nervousness. Very positive atmosphere between interviewers and the interviewee.	MS Teams	Calm environment at home and in the office. No background noises etc.	The interviewee was engaged and gave concise but detailed answers to the questions.
6	Sound was poor in the beginning as the interviewee was using a cell phone and was outside in an environment that was messy. Quality improved over time as the interviewee went inside to an office. Time was a limiting factor, and the interview was cut short and all questions were not answered.	MS Teams	There was an element of stress due to time constraint.	Many new ideas was presented in the interview
7	Good, on time and very specific answers with good motivation behind them. Answers provided for each question and very specific answers as well. Good environment, calm interview, no nervousness.	MS Teams	Calm environment at the office. No background noises etc.	No further comments
8	Good, and took less time than set aside. Good and concrete/direct answers provided. Good environment, calm interview, no nervousness. Very positive atmosphere between interviewers and the interviewee.	MS Teams	Calm environment at the office. No background noises etc. However, there were some problems with the sound quality in the beginning.	The interviewee did not have answers to all the questions in our questions in the interview guide since the field of work of the interviewee was not to perform risk analyses
9	Good interview overall - on time and provided specific answers to each question with good motivation behind them. Good environment, calm interview, no nervousness.	MS Teams	Calm environment from home. No background noises etc.	No further comments

Interviewee no.	How the interview went	Interview location	Environment	Other experience
10	Good interview and answers to all questions provided. However, a bit of stress from the interviewee as they had a time to stick to.	MS Teams	Calm environment from home. Some disturbances from the interviewee's side as someone came into the room and they also got a lot of messages during the interview which they attended to.	No further comments

10.8 Appendix H - Identification of Suitable Recommendations

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
No. 10: Make designers, risk assessors and decision makers aware of the limitations of the matrix and highlight difficulties with the tool. Be clear on the fact that the risk matrix may not be the best tool for decision making, but rather one of many methods supporting decision making. Acknowledge the following limitations of the risk matrix and view the tool with scepticism in mind: • A matrix should be designed in such a way that it is appropriate for the circumstances. This means that it may be difficult to standardize and apply a common system across a range of circumstances. • To define scales might be difficult with regards to unambiguity. • Different individuals might rate a risk differently, i.e., the use of the risk matrix can be subjective. • Aggregation is not possible (i.e., one cannot assess whether 5 "Low" risk scenarios are identical to one "Medium" risk scenario) • Application of a single value (or category) of consequences describing a hazardous scenario is made instead of a probability distribution of all possible consequences given a scenario – i.e., simplifications are made. • Risks with different categories of consequences are difficult to compare to one another or combine.	Risk matrices may generate ambiguity in results, but as they are so widespread and commonly used it is difficult to migrate to a different method. It is therefore better to acknowledge limitations and view the tool with scepticism. As each scenario might be subdivided into more detailed scenarios (leak from pipe vs leak from small hole in pipe) pushing it towards lower and lower frequency and hence yielding an accepted risk, it might not capture the true systemic risk. Further, aggregation is not possible and therefore one cannot determine systemic risk based on risks for individual scenarios.	Based on identified matrices it is unclear whether designers, risk assessors and decision makers are aware of the limitations of the matrix and know the difficulties with the tool. This recommendation may hence be applicable to all matrix types. There are indications that the limitations may not be known in practice, as data obtained points to the fact that decisions are made, and conclusions are drawn based on the risk matrix ranking in a HAZID only (e.g. "no showstoppers in the design" based on no red scenarios). Further, scenarios are selected for further investigation and assessed for need of added safeguarding (i.e., decided to be important or not important to assess) based on the risk matrix only as e.g., yellow scenarios are most often subject to LOPA whilst green ones are discarded. However, this might simply be a way of sorting out the most important scenarios and not actually directly making decisions. Based on identified matrices and use of them, this recommendation can be applicable and relevant for all risk matrix types. This due to data obtained pointing to the fact that sometimes conclusions are drawn based on the risk matrix ranking in a HAZID or HAZOP only (e.g. "no showstoppers in the design" based on no red scenarios). In other words, a conclusion regarding the whole system or design is made based on the assessment that no individual scenarios are within unacceptable levels.	There is awareness of the limitations of the risk matrix. For instance, subjectivity, appropriate matrix for the circumstances, difficulties with defining scales, not being able to show full system risk and the fact that decisions should not be based on outcome has been mentioned in the interviews when asked. No comparison between risks with different categories has been implied and aggregation has been discussed where interviewees implied that calibration should not be done for the risk matrix as the aim is not to assess sum of scenarios, but one scenario individually. Also, manipulation of values based on the detailed level of scenarios mentioned.	**Yes**. Even though there is some awareness based on the interviews, documentation sometimes indicates otherwise, and all limitations may not be known by each assessor and decision maker.

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
No. 12: Be aware of the fact that assignment of risk acceptance levels (i.e., which coloured section the scenario represents) for individual scenarios cannot determine the full picture of the risk picture (i.e., it is not possible to aggregate scenarios or determine risk on system level using risk matrices).				
No. 4: Consider the complexity of risks by adding a third or fourth dimension to the risk matrix (e.g., detectability, recoverability, strength of knowledge). Other factors than likelihood and consequence should be considered.	There is a weakness of the 2-D risk matrix approach in the fact that it does not visualize the complexity of risks, hence losing the full risk profile. Adding more dimensions will result in major hazard aversion being more clear, as high-consequence low-probability scenarios will be ranked higher as they also have low detectability.	Based on the data obtained regarding how the risk matrix is designed and used in practice, this recommendation might be practically applicable. All identified matrices are 2-dimensional looking at frequency and consequence only, hence relevant for matrix types 1-4.	• Practically difficult to add as user friendliness might decrease. • Strength of knowledge if adding any dimension • More uncertainty is introduced as the new dimension is also uncertain. • The added dimension might already be implicitly included in one of the other dimensions in mind (i.e. frequency is assessed with strength of knowledge in mind) - then adding it might be incorrect for the assessment as a whole. • Time consuming in workshop settings to cover just the two dimensions, let alone adding one more. • Unsure whether it would actually work in practice to add dimensions due to the fact that there are many things affecting the risks, but all cannot be captured - hence might not be very valuable to add another dimension. • The 2D risk matrix is seen as complex enough – adding another dimension will therefore add complexity where it is already considered high enough. • Understand it theoretically but has practical limitations. • Some are positive to this improvement as it showcases uncertainty which is oftentimes overlooked.	**No**. Theoretically good recommendation and could be applied to the identified matrices from documentation. However, practically not suitable due to time constraints, complexity etc as identified during interviews.
No. 5: Visualize uncertainty in a 2D matrix through e.g., adding prediction intervals or boxes together with colour schemes for epistemic uncertainty specifically. Further split the epistemic uncertainty into categories (data, model etc). Reference is made to Figure 7 and Figure 8.	Uncertainty, and especially epistemic uncertainty, has not been considered in the risk matrix, hence yielding a false picture that the input is more certain than it may be, leading to incorrect priority of risks.	Based on the data obtained regarding how the risk matrix is designed and used in practice, this recommendation might partially be applicable. Regarding visualization through prediction intervals, the practical application of risk matrices shows that the uncertainty is built into the interval length or width of the category. However, visualizing uncertainty regarding strength of knowledge (epistemic) similar to Figure 7 can be practically applicable if a third axis is not preferred as this is currently not the case for	• Theoretically a good idea and might be useful for showcasing results in a risk matrix from a QRA. • The prediction intervals are already part of the used intervals/categories of the matrix. In case of being in between two categories, the most conservative will be used. Hence, no added value of having prediction intervals in practice. • In a coarse risk analysis adding prediction intervals for both consequence and frequency could give added value in theory, but this is not worth the time it requires.	**No**. The proposed methods for visualization are not good enough even though they may be applicable to all identified risk matrices from documentation. However, showcasing uncertainty in some way may be beneficial. Further studies on how to showcase uncertainty may be relevant.

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
		the obtained risk matrices. Relevant for matrix types 1-4.	• It is already complex as is in coarse risk analyses – by adding this uncertainty in this detailed way will make the matrix too complex in the coarse risk analysis context. • However, might also save time as disagreements can be solved by people getting "one end each" in the interval. • **Proposes more anonymous risk analyses where participants can vote on the risk ranking to get a fair representation of intervals.** • Might be very cluttered if this is done for all scenarios in a PHA. Might be relevant for the worst scenarios, • There might be a discrepancy between which part of the interval is focused on - e.g., government representatives and the business side since the legislative representatives are more interested in the more conservative values and the business side is less conservative to limit costs. • Introduces complexity which reduces user friendliness. • Good idea to illustrate uncertainty in some way (arrows, intervals with both aleatory and epistemic in one interval), but this particular one is too complex. The complexity can decrease if this matrix type becomes a habit. Furthermore, as the matrix is still the standard one and the scenarios are showcased with dots as usual - hence those who do not understand the details of the circles can simply disregard them and understand the main result. • Some are positive to this improvement as it showcases uncertainty which is oftentimes overlooked. • Some interviewees like the proposed way of showcasing epistemic uncertainty. If uncertainty is high, it might be reasonable to continue with a more thorough analysis and this can be a way of catching this apart from where the scenario lays in the risk matrix. • Showcasing uncertainty gives the impression that the risk analyst/analyses has been done more thoroughly.	
No. 6: Make the risk matrix more comprehensible through a few simple visual improvements provided in Figure 6: Use non-linear scale labelling for matrices with exponential or otherwise	There has been too little empirical work on the effectiveness of risk matrices when it comes to supporting understanding and decision making. Further, there have been few studies on how	Based on the data obtained regarding how the risk matrix is designed, this recommendation can be practically applicable. No identified matrices have these types of visual tricks to improve perception,	• Generally positive to visual improvements, especially the recommendation of cell size increase. • Differing opinions on legends - some think it does not matter and legends can be used as more information	**Yes.** All identified matrix types from real life can benefit from *some* of the visual improvements as per this recommendation (e.g., type 2 only with regards to legends). The recommendation is also

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
non-linear increase (i.e., having likelihood categories labelled as 1, 10, 100, 1000 or 1,5,25,125,625 representing probabilities increasing with a factor of 10 or 5 at each step instead of having the categories labelled as 1,2,3,4). Logarithmic formatting of the cells may increase perception for those not familiar with risk matrices (i.e., increased cell size as the distance between each category increases). Consider a logarithmic formatting of cells. Integrate information directly into the risk matrix instead of using legends (under the assumption that the risk matrix will not become too cluttered).	different design choices affect understanding and efficiency of the tool.	hence relevant for matrix types 1-4.	is better to include than less. Some think legends should not be used due to the cognitive load of going between legend and matrix. • **Proposes that the risks can be visualized with larger dots/letters also instead of just cells. Also proposes that colouring should be done afterwards to decrease bias and the fact that many scenarios are yellow. This would increase objectivity.** • **Thinks just adding these visual improvements will not be enough. Wants examples of scenarios and where they are for comparison.** • Uncertainty whether it would add value to make visual improvements. • Increasing communication through visual aids is viewed positively and practically implementable.	deemed suitable and practically implementable according to what has been identified in the interviews.
No. 7: Counter centring bias by extending the range of categories.	Large enough categories might help reduce bias in the analysis. To counter centring bias, having more categories than necessary can be helpful.	Based on the data obtained regarding how the risk matrix is designed, this recommendation can be practically applicable. Based on identified matrices it is not possible to assess whether the categories are large enough or their range is wide enough to counter centring bias.	• Some confirm centring bias from real life experiences, whilst others do not. • Generally negative to extending axes as it increases complexity, is time consuming in a workshop setting the more categories one adds and might give false results (putting a scenario in a category that is just an extension and does not really exist) • Better to have stricter rules with regards to categories than "tricking" people into placing scenarios in the middle in an extended matrix • **Proposition to not show the matrix during the workshops to counteract biases, instead just asked about consequence and frequency which is afterwards added to a matrix. However, there might be difficulties with "openly" assessing these things without categories. This can be counteracted by asking "does this occur more often than 1 per 100 years" and if "yes" than "more often than 1 in 10 years".**	**No.** Even though centring bias is in some cases confirmed from interviews and from document studies - extending axis and increasing categories is not considered a suitable way to handle the problem practically. It increases complexity and time required in coarse risk analyses and skews results.
No. 8: Provide guidelines on the use of risk matrix in case of an event with several categories of consequences (e.g., consequences for both health, environment and financial).	There is a lack of guidance on how the matrix should be used - especially with regards to handling scenarios with several consequence classes.	Based on identified matrices it is not possible to assess whether guidelines are provided for how to handle an event with several consequence classes. Hence this recommendation might be applicable if guidelines have not been provided for matrix types 1-3.	• Guidelines are sometimes provided by the risk analysis leader or company. • No overarching guidelines for Sweden, but they do exist for other countries. • Differs how scenarios with several consequence dimensions are handled - some cover every dimension as a separate scenario, some only consider the worst case one.	**Yes.** Even though it seems from documentation that handling scenarios with several consequence dimensions in a HAZOP and LOPA is clear, guidelines are very important and should be issued according to interviews. They do not need to be general and can instead be suitable for the specific case and in accordance with the

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
		From projects identified where risk matrices have been used, the risks are ranked based on every class in the matrix as part of the HAZOP. Scenarios are then split and assessed individually in the LOPA - e.g., scenario 1s, 1a, 1e is the same scenario but 1s is the scenario with consequences for safety, 1a is the scenario with consequences for assets etc. 1a, 1s, 1e are hence further individually subject to LOPA.	• Guidelines are very important as they provide a good basis for how the tool should be used. Otherwise subjectivity is increased, and people may not know what they are doing when assessing such scenarios. For instance, if safety is only studied and the scenario might be "green", while the environment category is "red" - this can be missed. • Important to note that some scenarios might still not fit the guideline. • Only limitation is possible that it takes time to create the guidelines and that they have to be of certain quality. • Guidelines are not always necessary as it can be a dialogue between client and company (prior to the risk analyses) on how to handle these types of scenarios. • **Proposition from several interviewees to have a rule-set for handling scenarios with several consequence dimensions.** • There might be problems with having too rigid guidelines as they might become irrelevant for a specific plant. • Even though it was clear how the risk matrix should be used in cases of scenarios with several consequence dimensions, guidelines were still considered important as they would "cement" what is already clear.	client or company - i.e., not necessarily standardized. Reference is made to recommendation regarding which type of consequence is assessed (worst case, most likely etc) - this should be part of the provided guidelines.
No. 9: Clarify how risks that have the same score/position in the matrix should be prioritized.	There was no evidence found on which of the risks should be given priority when several risks have the same risk score.	Based on identified matrices and use of them, this recommendation may not be relevant or applicable. This is because when risks are ranked, they are ranked based on colour and not risk score/cell. Therefore, it would not be of value to e.g., clarify how two scenarios with the same score in a yellow cell are distinguished since they would both be taken from HAZOP to LOPA in practice or valued equally in a HAZID.	• Usually not prioritized differently, however for scenarios where it is easier to act or do something about it - this can be added as a recommendation in a HAZID or go to LOPA from a HAZOP. Whilst a scenario in the same cell where it is residual risk and might not be given any recommendation. • Differentiation is sometimes made if scenarios are of different consequence dimensions - then one scenario of one dimension might be prioritized over another. • Same risk ranking in practice means that scenarios will have the same priority and be handled with the same procedures. • Guidelines should be part of governance and not risk analysis, hence is not relevant in practice to differentiate between scenarios in the same cell in the risk matrix. • No practical need to provide guidelines for prioritization of scenarios in the same cell	**Yes**. Based on documentation it did not seem valuable to apply this recommendation. However, some interviewees state that prioritization is made in reality based on consequence type (e.g., asset is not as prioritized as safety/environment)and on how easy it is to do something about the scenario. As there were no guidelines available for how this prioritization is done but it still occurs in practice, and the recommendation does not increase complexity, uncertainty, or time – it is deemed suitable in order to increase uniformity in how prioritization is made.

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
			as they will all be followed up regardless if they are yellow/red. • However, some interviewees state that prioritization is made in reality based on consequence type (e.g., asset is not as prioritized as safety/environment)and on how easy it is to do something about the scenario. No guidelines available for how this prioritization is made. • Some interviewees consider it important to add guidelines as the prioritization is made in one way or another regardless – hence, unifying this through guidelines can be of value. Note also that the guideline can simply be that scenarios in the same cell should not be prioritized differently.	
No. 11: Consequence mapping should be done prior to likelihood mapping in risk analysis when using risk matrices and clarify which consequence is assessed (e.g., "typical" or worst case).	This in order to counteract the fact that depending on which consequence is identified (.e.g., worst case or "typical"), the frequency will differ.	Based on identified matrices and use of them, it is not possible to assess whether the consequences or frequencies are mapped first, and which consequences are assessed. Hence, this recommendation may either not be relevant (already implemented) or still relevant.	• Most often consequence is mapped first, and it is the worst credible one, but most likely also occurs. Some identify both. • Frequency is identified based on consequences, but some identify it based on the initiating event only. • Frequency is sometimes assessed first without safeguards in mind (i.e., all the way to the consequence), and then with safeguards taken into consideration. • Regardless, it is clear which consequence is assessed in the analysis even if no guidelines are provided as it is most often worst credible if not otherwise agreed with the client. • However, there are interviewees mentioning that it is not clear which consequence is actually assessed. • Could be of value to be clear on the fact which consequence is assessed. • From practice, it is not always clear which consequence has been assessed when looking at the results in the risk matrix.	**No**. From documentation, it was not possible to assess whether the recommendation was suitable or not. From interviews, it is seen that the consequence is usually mapped first. However, it does not seem to matter if consequence or frequency is mapped first if the result of the analysis is satisfactory and understandable (i.e., clearly stated that the frequency is for the initiating event only). However the consequence that is actually mapped should be specified in the guideline as it is in some cases unclear based on the interviews.
No. 13: Do not have a large variety of risk matrices within the same company and industry, if there are not different risk appetites or a clear motivation for the specific risk matrix. specific risk matrix. (However, it shall be noted that the risk matrix should be appropriate for the circumstances).	Different risk matrices may yield different outcomes for the same scenario (i.e., standardization) under the same circumstances. A large variety of risk matrices have been used, but no explanations were found to justify the use of one specific risk matrix. Depending on which matrix was used, different results were given for the same scenarios.	Based on identified matrices and use of them, this recommendation might not be very relevant or practicably applicable. Most matrices have been corporate. It is not possible to assess whether there have been clear motivations of differentiation.	• Various risk matrices are used - both corporate and project specific/ "standard". • Sometimes unclear why a specific matrix is used. Sometimes it has simply been "copy-pasted" from another company/industry. • Sometimes the matrix gets updated solely based on trends and on the interests of the HSE manager (e.g., from a 3x3 to 5x5), • Sometimes differentiation is actually motivated by calibration to the company's	**Yes**. From documentation it did not seem necessary as mostly corporate risk matrices were identified. However, based on the interviews, it was clear that a large variety of risk matrices is present without always having a motivation for why it has been used. There should be motivation for why a certain matrix is used and the matrix should be suitable for its purpose (e.g., not "copy-pasted" from another industry).

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
			specific risk acceptance, geographic location etc. • Some have seen that risk matrices have sometimes been created by a third party, and in that case, it may not be very motivated with regards to what the company assesses to be accepted risk/not accepted risk. Thinks there is practical need to motivate the risk matrix in reality (however motivation can simply be that the company has agreed on this).	
No. 14: Consider transforming qualitative axes of the risk matrix to quantitative grading e.g., through fuzzy logic.	As different people understand the meaning of linguistic terms differently, converting these linguistic terms to quantitative values will improve objectivity and give clearer results.	Based on identified matrices and use of them, this recommendation might be applicable to matrix type 1-4 as they all have purely qualitative elements. However, the approach fuzzy logic might be too advanced to practically implement as it requires obtaining data regarding what different linguistic terms mean for a variety of personnel. Hence it might not be practicably applicable.	• Differing opinions. Some prefer quantification but some want to expand on qualitative descriptions. • Interviewees not positive to quantification mean that it can be better to have a more detailed qualitative description for some consequences as they are not quantifiable (requiring first aid is better description than simply giving this a number). This is because participants in a workshop can relate easier to qualitative description (based on experience) as well as quantification giving the idea of something being more certain than it is. • Interviewees positive to quantification mean that quantifying removes subjectivity which is positive as the linguistic uncertainty is removed. • Some prefer quantitative axes up to numbers in the range of 10^-3-10^3, after that it is difficult to understand numbers according to this interviewee – hence clear qualitative descriptions such as “has never occurred in the industry” is better for very small/very large values. • Regardless, all mention that the most important thing is that labels are clear and not subjective (e.g., “major” consequences need to be described either in numbers or clearly with words as e.g., “one week spent in hospital”).	**No.** There are already some of the matrices that are semi-quantitative, some are qualitative with austere descriptions of the categories from the documentation From interviews it is given that the transformation may give the impression that the result is more certain that it is. However, to limit subjectivity and make the axis more understandable, proper descriptions are important. If it is possible to define the categories with numbers to make the matrix semi-quantitative, it can be preferred. However, this recommendation is not preferred if qualitative detailed descriptions are possible.
No. 15: If the risk matrix is used within a process hazard analysis (PHA), calibrate the risk matrix with regards to risk acceptance, where the individual or group risk criteria is divided by the estimated number of hazardous scenarios leading to the same hazard.	Risk matrices used for deciding upon relevant risk reduction are often based on numerical values. If the acceptance criteria for the overall facility is used to rank individual scenarios, but there are multiple ones leading to the same hazard, the sum of these scenarios may lead to unacceptable risk level	Based on identified matrices and use of them, this recommendation might be applicable as many risk matrices identified were used in PHAs and were corporate - i.e., not calibrated for the specific project.	• Uncertain if matrices are calibrated. Most likely not. If it is calibrated, it has happened implicitly over time with natural updating of the matrix. • Some mention that the used risk matrix has been calibrated way back based on presumed number of hazardous scenarios in line with this methodology. So, this is the foundation of the matrix.	**No.** From documentation it was implied that matrices for PHAs were not calibrated. From interviews, it was clear that this recommendation would not be suitable and practicable due to introduction of uncertainty and time- constraints in case of need for re-calibration. The point of analysing one scenario at a time in the workshop (not systemic risk) was also mentioned as a

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
			• Not positive to calibration as one scenario should be assessed individually. However, it is mentioned that if calibration is easily done it might be of value. • However, some interviewees say that if the calibration can be performed – it is of value, as it can help to see the risk of the sum of scenarios. • Calibration introduces uncertainty as one cannot know the number of scenarios to calibrate for beforehand. Therefore, it might be time consuming to go back and forward after the risk analysis to re-calibrate. Hence, practically not applicable due to time constraints. • Also gives the impression of being more certain than it is. • Might also be practically unnecessary to calibrate as one can see if many scenarios occur in one area and do an assessment whether that is acceptable or not, instead of calibrating the whole matrix. • If calibration of the matrix is done, it should be on a higher level (calibrating with regards to company and industry type - e.g., categories for fish farming might differ from categories for oil and gas and this should be calibrated for)	motivation against this recommendation.
No. 1: Establish the risk matrix with decision maker's risk appetite in mind. (e.g., through a utility function). No. 2: Consider having a continuous probability-consequence diagram instead of gridding the matrix as this will improve resolution. Visualize uncertainty through size of boxes as this will improve major hazard aversion. Reference is made to Figure 7. No. 3: If the risk matrix is to be used for prioritization of risks, consider using the Sequential Updating Approach (SUA) for defining the rating schemes (number of ratings/colours used in the matrix and how to assign these to different cells).	During establishment of the risk matrix, there is a lack in consideration of risk attitudes of decision makers. There is a resolution problem, uncertainty is not visualized, and major hazard aversion is not taken into account. A continuous probability-consequence diagram will yield better visualization, deal with the resolution problem, visualize uncertainty and incorporate major hazard aversion. This is an approach which will help with the resolution problem and define cells in such a way that it is possible to logically compare scenarios between cells in a logical manner.	It is not possible to assess from documentation whether acceptance levels have been based on decision makers or something else (e.g., best industry practice) What has been seen in practice, is that the assessment of scenarios from e.g., HAZOPs and HAZIDs are done based on the colour scheme of a specific cell. It is not possible to assess from documentation whether it would create additional value to identify exact values for probability and consequence using a continuous PCDS. This approach might create more grids and colours in the matrix. Based on practical applications of risk matrices, the colours are used for assessment. Having more colours might create value but might also simply mean that "both yellow and orange" go to LOPA.	• Some interviewees had created or been part of the creation of new matrices, others had not. • Sometimes the matrix was based on earlier experience and industry specific categories. Sometimes it was simply copied without thought behind it. • Colours and gridding were assigned arbitrarily without decision makers input. Other times risk acceptance was anchored with the facility or risk acceptance criteria. • Some interviewees find it very important that the risk matrix is line with the values of the company and that this matrix is used all over the company. The values should correlate to best industry practice. • Mentioned that there should be fewer categories if the matrix is used in a workshop setting. • Continuous consequence-probability diagram not suitable for workshop settings. However it can be of value for representing scenarios in QRA even if that is not industry practice.	No . 1:**Yes.** It was not possible to assess from the documentation alone if the acceptance levels reflected decision maker attitudes. There was no clear answer given in the interviews and there were contradicting answers given. Some of the interviewees said that there was some input given by decision makers (or client) while others expressed the opinion that this was not necessary as long as the matrix corresponded to best industry practice.). However, some interviewees presented a strong opinion that the decision maker attitudes should be reflected in the acceptance level – on the premise that they are in line with best industry practice As it was done for some matrices, this is enough evidence that it is practically applicable. Together with the strong opinions of the interviewees – this recommendation is deemed suitable. No. 2: **No**. Even though continuous probability consequence diagrams were not identified in documentation and therefore may be applied, the

No. Recommendation	Motivation for recommendation	Result from documentation	Result from interview	Relevant recommendation?
			• Some prefer continuous diagrams to reduce centring bias and promote decisions. • SUA not relevant as the gridding should be as minimal as possible in a workshop setting. It might increase complexity to use more categories. • Some think it is important that the risk acceptance reflects the opinions of the decision makers, whilst others do not consider it important. It should be instead based on knowledge and best industry practice.	interviews indicated that there was almost no one who preferred continuous probability consequence diagrams. This due to the fact that it increases complexity and might be too time consuming to decide upon precise values in a workshop setting. Generally, more simple matrices are preferred. No. 3: **No.** From documentation it seems that colours are used for assessment - adding more of them might not add value. From interviews, SUA is not deemed relevant as the gridding should be as minimal as possible in a workshop setting. It might increase complexity and required analysis time to use more categories.
What is your relation to the risk matrix?	N/A		Generally positive attitude towards the risk matrix, but with the notion that it should be used with a stated intent, the user should be aware of the limitations, and it should be a part of an analysis not the sole method. Generally want the risk matrix to be simple as it is most often intended as a first sorting out of scenarios to look further into. That's where the strength of the method lies, simplicity! The interviewees are generally positive to the suggested improvements in theory, but not if they are at the expense of simplicity, time and user friendliness. More information should be provided on the use of the matrix. One positive feature is that it can be understood by everyone. If it becomes too complex, this feature is lost. The purpose should be to highlight and present the results of a course analysis and the performers of the analysis should be professionals with high integrity. Some interviewees propose to do risk ranking after the workshop, and maybe then add the complex recommendations (intervals, third axis etc).	