Dag Eirik Nordgård

Risk Analysis for Decision Support in Electricity Distribution System Asset Management

Methods and frameworks for analysing intangible risks

Thesis for the degree of Philosophiae Doctor

Trondheim, April 2010

Norwegian University of Science and Technology
Faculty of Information Technology, Mathematics
and Electrical Engineering
Department of Electric Power Engineering

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PREFACE

"One, two, three, four!"[1]

This thesis is submitted as a part of the fulfilment of the requirements of the degree philosophiae doctor, PhD, at the Department of Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim.

The work leading to this thesis was performed during the period August 2006 – November 2009. Professor Ivar Wangensteen from the Department of Electrical Power Engineering, NTNU, was the main supervisor, while Kjell Sand, senior researcher at SINTEF Energy Research and adjunct professor at NTNU, was co-supervisor. During the autumn of 2009, Kjell Sand acted as the main supervisor during Ivar Wangesteen's sabbatical leave.

The thesis has been written as a part of the project "Risk based distribution system asset management" (RISK DSAM), funded by the Research Council of Norway and companies within electricity distribution in Norway, France and Sweden.

Trondheim, December 2009

Dag Eirik Nordgård

[1] The count-in for *I saw her standing there*, the first song on the first album by The Beatles, *Please Please Me*, issued 1963.

ACKNOWLEDGEMENTS

"With a little help from my friends"[2]

As I approach the end of the work leading up to this thesis, I would like to acknowledge some individuals for their contributions to the process.

First, I would like to thank my supervisor, Professor Ivar Wangensteen, for the discussions and guidance he offered throughout the work. I would also like to sincerely thank my co-supervisor Kjell Sand at SINTEF Energy Research for his advice and cooperation over these years.

Undertaking a PhD work is in many ways a journey on a long and winding road, and I would like to send my heartfelt appreciation to family, friends and colleagues for their interest, support and encouragement. In particular I would like to thank Maren Istad and Maria D. Catrinu for their contributions on several papers and their comments during the process of writing this thesis; and Jørn Heggset, Thomas Welte, Knut Samdal, Oddbjørn Gjerde and Agnes Nybø for contributing to my work by co-authoring papers. I would also like to thank Eivind Solvang for inspiring discussions concerning risk and risk management in electricity distribution asset management.

I would also like to acknowledge Professor Emeritus Arne T. Holen, for his help during the preparation of one of the papers presented in this thesis. The collaboration and discussions with Geir Solum at Trondheim Energy are also highly appreciated.

I also express my gratitude to the companies participating in the RISK DSAM project, and to SINTEF Energy Research, represented by research director Petter Støa, for supporting my PhD work. Without their backing it would not have been possible for me to take on this task.

Last – and largest – I would like to thank my family: My wife Hanne - for her love and support (and proofreading…), and for showing interest in and patience with my work. And our two sons, Øystein and Bjørnar - for inspiration, recreation and joy; and for helping daddy keep in mind the truly important things in life…

Dag Eirik Nordgård

[2] Song by John Lennon and Paul McCartney, issued on the *Sgt. Pepper's Lonely Hearts Club Band* album, 1967.

SUMMARY

"Here comes the sun"[3]

During the last 10 to 15 years electricity distribution companies throughout the world have been ever more focused on asset management as the guiding principle for their activities. Within asset management, risk is a key issue for distribution companies, together with handling of cost and performance. There is now an increased awareness of the need to include risk analyses into the companies' decision making processes.

Much of the work on risk in electricity distribution systems has focused on aspects of reliability. This is understandable, since it is surely an important feature of the product delivered by the electricity distribution infrastructure, and it is high on the agenda for regulatory authorities in many countries.

However, electricity distribution companies are also concerned with other risks relevant for their decision making. This typically involves intangible risks, such as safety, environmental impacts and company reputation. In contrast to the numerous methodologies developed for reliability risk analysis, there are relatively few applications of structured analyses to support decisions concerning intangible risks, even though they represent an important motivation for decisions taken in electricity distribution companies.

The overall objective of this PhD work has been to explore risk analysis methods that can be used to improve and support decision making in electricity distribution system asset management, with an emphasis on the analysis of intangible risks.

The main contributions of this thesis can be summarised as:

- An exploration and testing of quantitative risk analysis (QRA) methods to support decisions concerning intangible risks.
- The development of a procedure for using life curve models to provide input to QRA models.
- The development of a framework for risk-informed decision making where QRA are used to analyse selected problems.

In addition, the results contribute to clarify the basic concepts of risk, and highlight challenges related to risk terminology, risk perception and risk communication that are

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[3] Song by George Harrison, issued on the *Abbey Road* album, 1969.

relevant to electricity distribution companies in their asset management. The work has also exemplified that it is hard to find statistical data sources that can provide the basis for numerical estimates of model parameters when analysing intangible risks. The use of expert judgment to estimate model parameters is hence of great importance.

When dealing with risk analysis, it should be kept in mind that uncertainty about future outcomes is one basic prerequisite for risk. This uncertainty can be explored through risk analyses, but it can never be eliminated. The aim of risk analysis should therefore be to contribute to problem understanding and to make robust decisions, rather than trying to provide the "right" answer.

The results presented in this thesis show that quantitative risk analysis can provide useful decision support, for example through making it easier to compare alternatives in a decision situation. It will however require more labour compared to simplified risk analysis, and QRA should therefore be used with some caution.

THE STRUCTURE OF THE THESIS

"Paperback writer"[4]

This thesis is written for professionals and scientists with knowledge and understanding of the basic – and sometimes more advanced – concepts of electricity distribution system asset management. Some basic knowledge about risk and risk management would also be favourable to help the reader to understand the findings.

The thesis consists of two parts: *Part I – Main report* and *Part II - Papers*.

Part I – Main report summarises the work that has been done, and highlights the main results and contributions.

Chapter 1 introduces the background for the work, and the motivation for the selection of research area. The objectives and delimitation of the work are also stated here. Chapter 2 describes the scientific approach for the work and the context in which the work has been performed. In Chapter 3, the concepts of asset management are presented, followed by an introduction to risk and risk management in Chapter 4.

Chapter 5 summarises the main results from the work, with reference to the papers where the details are documented. The intention is that it should be possible to read *Part I - Main report* separately and get an overview of what is treated in more detail in the papers. Therefore, examples and descriptions from the papers are included in Chapter 5, in order to enhance the understanding and readability of this chapter.

Chapter 6 discusses the results, before conclusions and ideas for further work are presented in Chapter 7.

Part II – Papers consists of seven papers already published or submitted to international conferences or journals. The papers describe different parts of the topics addressed in this thesis, and they are listed in the next section, together with comments concerning the author's[5] contributions to each.

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[4] Song by John Lennon and Paul McCartney, issued on the *Paperback writer*/*Rain* single, 1966.
[5] "The author" refers to the author of this thesis, Dag Eirik Nordgård.

PAPERS INCLUDED IN THE THESIS

Paper I. "**Application of Bayesian belief networks in electricity distribution system maintenance management**". Dag Eirik Nordgård and Kjell Sand. In the proceedings of the ESREL / SRA conference 2008, Valencia (Nordgård and Sand, 2009).

The paper was written mainly by the author. Co-author Kjell Sand contributed with the initial description of Bayesian Networks in section 3, and to rephrase parts of section 1, Introduction, and section 5, Concluding remarks. The structure of the paper was also discussed with Ivar Wangensteen. Input and suggestions from the ESREL reviewers were also used to improve the paper.

Paper II. "**Quantitative Risk Assessment for decision support in electricity distribution asset management**". Dag Eirik Nordgård. Submitted to the European Transactions of Electrical Power (Nordgård, 2009a).

The paper was written solely by the author. Professor Emeritus Arne T. Holen, NTNU, contributed with thorough comments concerning the structure and contents of the paper. The structure of the paper was also discussed with Kjell Sand and Ivar Wangensteen.

Paper III. "**Exploring uncertainty in quantitative risk assessment used for decision support in electricity distribution system asset management**". Dag Eirik Nordgård. In the proceedings of the ESREL conference 2009, Prague (Nordgård, 2010).

The paper was written solely by the author. Input and suggestions from the ESREL reviewers were used to improve the paper.

Paper IV. "**Using Life Curves as Input to Quantitative Risk Assessment in Electricity Distribution System Asset Management**". Dag Eirik Nordgård, Thomas Welte and Jørn Heggset. Accepted by the Journal of Risk and Reliability (Nordgård et al., 2010b).

The paper was written in cooperation with Thomas Welte and Jørn Heggset, both at SINTEF Energy Research. They have contributed with the formulation of the problem and the writing of sections 2.2-2.4 concerning life curve modelling approaches. They have also carefully read and commented on drafts during the development of the paper.

Paper V. “**Risk assessment methods applied to electricity distribution system asset management**”. Dag Eirik Nordgård, Kjell Sand and Ivar Wangensteen. In the proceedings of the ESREL conference 2009, Prague (Nordgård et al., 2010a).

The paper was written mainly by the author. The initial description of section 4 was written by Kjell Sand based on (Sand et al., 2007). Co-authors Kjell Sand and Ivar Wangensteen further contributed with comments on draft versions of the paper. Input and suggestions from the ESREL reviewers were also used to improve the paper.

Paper VI. “**A Framework for Risk-Informed Decision Support in Electricity Distribution Companies utilizing input from Quantitative Risk Assessment**”. Dag Eirik Nordgård. Submitted for International Journal of Electrical Power & Energy Systems (Nordgård, 2009b).

The paper was written solely by the author. The structure and contents of the paper were discussed with Maren Istad, NTNU / SINTEF Energy Research. Ivar Wangensteen and Kjell Sand contributed with comments on draft versions of the paper.

Paper VII. “**Risk communication and perception challenges in electricity distribution maintenance and reinvestment management**”. Dag Eirik Nordgård. In the proceedings of the Nordic Distribution and Asset Management Conference, NORDAC 2008, Bergen (Nordgård, 2008b).

The paper was written solely by the author. An early version of the contents of the paper was discussed with Professor Britt-Marie Drottz Sjöberg, Department of Psychology, NTNU.

ADDITIONAL PAPERS

In addition to the papers included in Part II of this thesis, the author has written or co-written several papers about different aspects of risk analysis and asset management during the PhD work.

These papers are not included in this thesis, but are listed in the following. Results from and reference to some of them are used in *Part I – Main report*.

- "**Establishing a risk-based maintenance strategy for electricity distribution companies**". Dag Eirik Nordgård and Knut Samdal. In the proceedings of the ESREL conference 2009, Prague (Nordgård and Samdal, 2010).
- "**Incorporating risk analysis and multi-criteria decision making in electricity distribution system asset management**". Maria D. Catrinu and Dag Eirik Nordgård. In the proceedings of the ESREL conference 2009, Prague (Catrinu and Nordgård, 2010).
- "**Experiences using Quantitative Risk Assessment in Distribution system asset management**". Dag Eirik Nordgård and Geir Solum. In the proceedings of the CIRED conference 2009, Prague (Nordgård and Solum, 2009).
- "**Risk Assessment as an Integrated Part of Distribution System Reinvestment Analysis**". Oddbjørn Gjerde and Dag Eirik Nordgård. In the proceedings of the CIRED conference 2009, Prague (Gjerde and Nordgård, 2009).
- "**Enabling a national service provider market for distribution network maintenance services**". Knut Samdal, Dag Eirik Nordgård, Geir Solum and Kåre Espeland. In the proceedings of the CIRED conference 2009 (Samdal et al., 2009).
- "**Risk Assessment as an Integrated Part of Distribution System Reinvestment Project Analysis**". Oddbjørn Gjerde and Dag Eirik Nordgård. In the proceedings of the Nordic Distribution and Asset Management Conference, NORDAC 2008, Bergen (Gjerde and Nordgård, 2008).
- "**Reinvestment strategies for distribution networks**". Maria D. Catrinu, Agnes Nybø and Dag Eirik Nordgård. In the proceedings of the Nordic Distribution and Asset Management Conference, NORDAC 2008, Bergen (Catrinu et al., 2008).
- "**Quantitative risk assessment in distribution system maintenance management using bow-tie modelling**". Dag Eirik Nordgård. In the proceedings of the Power System Computation Conference (PSCC) 2008, Glasgow (Nordgård, 2008a).

- "**Risk Based Decisions for Reinvestments in Distribution Systems**". Maren K. Istad, Dag Eirik Nordgård, Oddbjørn Gjerde, Maria D. Catrinu, Agnes Nybø and Bjørn E. Birkeland. In the proceedings of PMAPS - 10th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS) 2008, Rincón, Puerto Rico (Istad et al., 2008).

- "**A risk based approach to electricity distribution system asset management**". Dag Eirik Nordgård, Maren K. Istad and Kjell Sand. In the proceedings of the EuroMaintenance conference 2008, Brussels (Nordgård et al., 2008).

- "**A risk based approach to Distribution System Asset Management and a survey of perceived risk exposure among distribution companies**". Dag Eirik Nordgård, Kjell Sand, Oddbjørn Gjerde, Maria D. Catrinu, Jukka Lassila, Jarmo Partanen, Sylvie Bonnoit and Jean Aupied. In the proceedings of the CIRED 19th International Conference on Electricity Distribution 2007, Vienna (Nordgård et al., 2007a).

- "**Multi-criteria decision support in distribution asset management**". Maria D. Catrinu, Dag Eirik Nordgård, Kjell Sand and Jane K. Norhagen. In the proceedings of the CIRED 19th International Conference on Electricity Distribution 2007, Vienna (Catrinu et al., 2007).

- "**Establishing maintenance standards following a risk based maintenance strategy**". Dag Eirik Nordgård, Geir Solum, Lennart Heggdal, Erik Omdal, Jon Inge Fjellsbø and Arne Birger Sjursø. In the proceedings of the CIRED 19th International Conference on Electricity Distribution 2007, Vienna (Nordgård et al., 2007b).

- "**Risk assessment gives better maintenance management"** *(In Norwegian)* Dag Eirik Nordgård. Elektro, nr 4/2007 (Nordgård, 2007).

- "**Establishing a risk-based maintenance strategy for distribution companies"** *(In Norwegian)* Dag Eirik Nordgård and Geir Solum. In the proceedings of NEF Teknisk møte, Trondheim March 2007 (Nordgård and Solum, 2007).

NOTATION

"The word"[6]

Important words and phrases

Risk	The combination of the probability of an event and its consequence (ISO/IEC, 2002).
Intangible risk	For the purpose of this thesis, *intangible risk* is used to denote risks whose consequences are hard to quantify in economic terms, even though it is possible to measure them in other terms. *Intangible risks* particularly refer to risks related to safety and environmental impact, but the term can also include reputational risk, political risks and similar.
Performance	For the purpose of this thesis, *performance* is used to denote how well a distribution company achieves results with regards to given criteria, e.g. financial aspects, health and safety aspects and environmental aspects. *Performance* denotes what is actually achieved, in contrast to *risk* which focuses on potential future outcomes.
Risk analysis	Systematic use of information to identify and to estimate the risk (ISO/IEC, 2002).
Risk assessment	Overall process of risk analysis and risk evaluation (ISO/IEC, 2002).
Risk management	Coordinated activities to direct and control an organization with regard to risk (ISO/IEC, 2002).

Abbreviations

BN (BBN)	Bayesian Network *– in some cases referred to as Bayesian Belief Network (BBN)*
CENS	Cost of Energy Not Supplied. Norwegian regulation concerning customer interruptions.
CPT	Conditional probability table

[6] Song by John Lennon and Paul McCartney, issued on the *Rubber Soul* album, 1965.

DSAM	Distribution System Asset management
DSB	Direktoratet for samfunnssikkerhet og beredskap *Directorate for Civil Protection and Emergency Planning*
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and operability analysis / study
LV	Low Voltage (< 1 kV)
MCDM	Multi Criteria Decision Making
MV	Medium Voltage (1 – 36 kV)
NPV	Net Present Value
NTNU	Norges Teknisk-Naturvitenskapelige Universitet *Norwegian University of Science and Technology*
NVE	Norges vassdrags- og energidirektorat *Norwegian Water Resources and Energy Directorate*
PAS 55	Publicly Available Specification 55, (BSI, 2008a) and (BSI, 2008b)
PDCA	Plan-Do-Check-Act (principles of continual improvement)
PLL	Potential Loss of Life
QRA	Quantitative Risk Analysis
RISK DSAM	Risk Based Distribution System Asset management, a competence building project at SINTEF Energy Research of which this PhD-work is a part. www.energy.sintef.no/prosjekt/RISKDSAM

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PART I – MAIN REPORT

1 INTRODUCTION

"…may I introduce to you, the act you've known for all these years…"[7]

This chapter gives a brief introduction to the background for the work presented in this thesis, and also introduces some of the topics addressed. It also outlines the objectives for the work, along with the delimitation and scope.

1.1 BACKGROUND

Electricity distribution is a vital part of the infrastructure of modern society. In industrialized countries, most of the electricity distribution systems already exists as an infrastructure - most of which has been built during the last 50 years. Hence, electricity distribution companies are now faced with the challenges associated with managing a generally ageing infrastructure, see e.g. (Hughes, 2005, Sinclair, 2009).

During the last 10 to 15 years, electricity distribution companies throughout the world have been ever more focused on *asset management*[8] as the guiding principle for their activities – see e.g. (Kostic, 2003, Brown and Spare, 2004, Berende et al., 2009, Pschierer-Barnfather, 2009).

The concept of asset management in general has developed during this same period of time, and reflects input from a number of industrial sectors – such as water supply, transportation and energy supply. All of these sectors share a reliance on an infrastructure of physical assets that provides the foundation for their businesses (BSI, 2008a, BSI, 2008b).

Asset management in electricity distribution companies is about the complex balancing of *cost*, *performance* and *risk* – taking into account various aspects such as economic performance, quality of supply, safety and environmental impact (Brown and Humphrey, 2005, Hughes and Pears, 2007). These aspects may constitute counteracting drivers in a decision making context and there is a need for structured methods to

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[7] Text line from the song *Sgt. Pepper's Lonely Hearts Club Band* by John Lennon and Paul McCartney, issued on the *Sgt. Pepper's Lonely Hearts Club Band* album, 1967.
[8] The origin of the term *asset management* is from economics, referring to composition of an institution's financial assets – e.g. its portfolio of loans, securities, and cash. The *assets* may also be extended to include also intangible assets such as company reputation and market trust.

analyse and evaluate them – in order to support asset management decisions. Together with handling cost and performance, the management of risk is therefore a key issue for electricity distribution companies, and there is now an increased awareness about taking risk assessment into account in the decision making context (Sinclair, 2009).

Risk analysis methods have evolved significantly since the mid 1960's (Bernstein, 1996). In electricity distribution system management, there has been much focus on developing reliability analyses, see e.g. (Fangxing and Brown, 2004, Janjic and Popovic, 2007, Bertling et al., 2005). This focus is understandable, since reliability of supply surely is an important feature of the product delivered by the electricity distribution infrastructure and a focus for regulatory authorities in many countries (Eurelectric, 2005).

However, electricity distribution companies are also concerned with other important risks that are relevant for their businesses.

In a survey presented in (Sand et al., 2007), different risk consequence categories for distribution companies are grouped into the following:

- Economic risk,
- Safety risk,
- Environmental risk,
- Quality of supply risk,
- Reputational risk,
- Vulnerability risk, and
- Regulatory risk.

Several of these consequence categories are what can be called *intangible risks*[9] – meaning that they can be hard to quantify, at least in economic terms. Safety, environmental impacts and company reputation impact are typical examples of this, see e.g. (Sand et al., 2007, Hughes, 2005, Hamoud et al., 2007). It should also be noted that several of the consequence categories can be related and overlapping. For example, safety and environmental issues may have a significant impact on company reputation.

In some cases, intangible risks are made tangible by converting the consequences to a common measure – usually money. An example of such an approach is presented in (Hughes et al., 2009), where network performance and environmental, safety and financial consequences are merged into one economic risk measure. This raises difficult ethical questions, such as the quantification of the economic value of human health, as

[9] For the purpose of this thesis *intangible risk* is used to denote risks whose consequences are hard to quantify in economic terms; even though being possible to measure in other terms (e.g. litres oil spilled, potential loss of life etc.). *Intangible risks* cover specially risks related to safety and environmental impacts, but the term can also include reputational risk, political risks and others.

discussed in e.g. (Vatn and Aven, 2009). There is no easy answer to this with regards to what is right or wrong. In the work presented in this thesis, the consequences of intangible risks have deliberately not been converted into economic terms, but rather each risk has been analysed on its own – with the goal of using the results as input to a formal or informal multi-criteria decision framework in the final decision, for example as described in (Nordgård et al., 2003, Istad et al., 2008, Catrinu and Nordgård, 2010).

In contrast to the numerous methods developed for reliability calculations and decision support (Billinton et al., 2001, Schilling et al., 2009), there are few applications of analyses to support decisions concerning intangible risks. This is a bit of a paradox, since such risks represent an important motivation for decisions taken in electricity distribution companies.

Hence, there is a need to find and develop methods to analyse and evaluate also the intangible aspects of the electricity distribution companies' risks. This is one of the driving motivations for the research project *Risk based Distribution System Asset management*, RISK DSAM[10] – of which this PhD work is a part.

[10] RISK DSAM is a competence building project sponsored by the Research Council of Norway in the RENERGI programme, and companies within electricity distribution in Norway, France and Sweden. The project started in 2006 and ends in 2010.

1.2 OBJECTIVES

The main objective for the work presented in this thesis was to explore risk analysis methods that can be used to support decision making in electricity distribution system asset management, with an emphasis on the analysis of intangible risks.

In order to make this objective more manageable, it has been divided into the following sub-objectives:

1. Describe the basic concepts of risk and risk management.
2. Elaborate on challenges related to risk communication and perception.
3. Test and evaluate methods for quantitative risk analysis for distribution system asset management decision support, focusing on bow-tie models and Bayesian networks. Included in this is to explore uncertainty in risk analysis.
4. Elaborate on challenges and possible solutions related to acquiring numerical input data for quantitative risk analyses.
5. Establish a framework for risk-informed decision making in distribution system asset management, emphasising the use of risk analysis, *and:*
6. Test and exemplify results from the above stated sub-objectives, through realistic cases.

The grouping of the sub-objectives is illustrated in Figure 1. The two lower parts of the figure represent general aspects of risk – including risk communication and perception, while the four other parts of the figure illustrate objectives that are more specific to applications in electricity distribution system asset management.

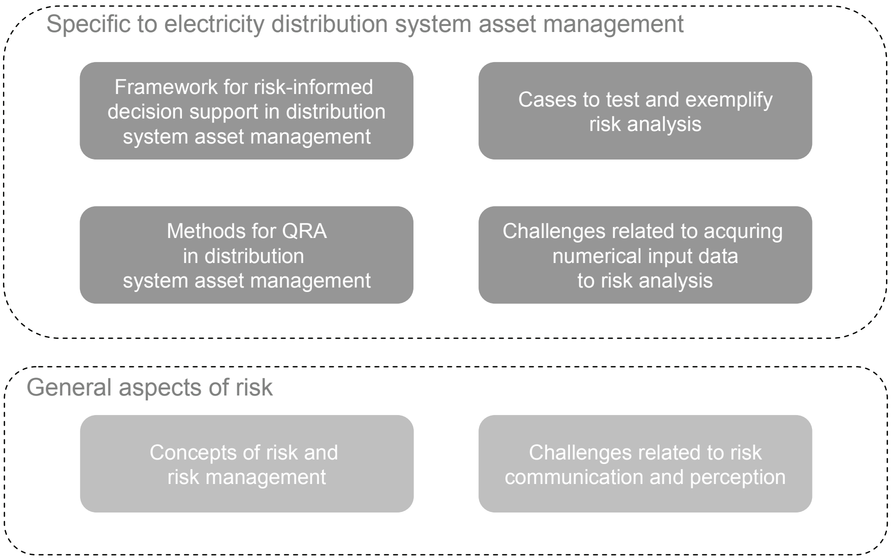

Figure 1 Schematic illustration of sub-objectives of the PhD work.

Each of the sub-objectives constitutes parts of the puzzle of risk-informed decision making in asset management. However, it should be noted that the sub-objectives do not provide the whole picture, but rather illuminate parts of it.

1.3 DELIMITATION

The work presented in this thesis mainly addresses challenges related to risk and risk management faced by electricity distribution companies in their asset management. The focus has been on analysing intangible risks - other than economic and reliability risks. Safety and environmental impacts are typical examples of such risks.

The operating framework that applies to Norwegian electricity distribution companies forms the background for the work. One example is the regulation of cost of energy not supplied, CENS, which makes risks related to reliability failure an economic risk for the distribution companies (Langset et al., 2001, Kjølle et al., 2008). This is also one motivation for not including reliability analysis in the analysis of intangible risks. This may typically not be applicable in other countries with other regulatory regimes, although similar penalty schemes are getting more common (CEER, 2008).

The ambition of the work has been to use existing risk analysis methods to provide decision support in this new area of application, with a focus on testing bow-tie models (combining fault tree and event tree analysis) and Bayesian networks. It has been beyond the scope of this PhD work to develop new risk analysis methods.

Throughout the work, the emphasis has been on the potential practical application of risk analysis methods in electricity distribution company decision making. This has motivated for a rather high-level approach, without going into detailed discussions about the computational concepts that apply to the methods.

Even though the work has been performed in this context, the results are not restricted solely to these applications and the overall thinking and concepts should be generally applicable to other risk related situations and to distribution companies in other countries.

2 ABOUT THE PHD WORK

"The long and winding road"[11]

This chapter describes the scientific approach that was used in the PhD work, and states the context in which the work was performed.

2.1 SCIENTIFIC APPROACH

This thesis addresses different aspects of risk management in electricity distribution system asset management, and the overall ambition of the research has been to address methods and topics that have potential for practical application in Norwegian electricity distribution companies.

Risk covers technical, sociological and psychological dimensions of the topic. The research has therefore involved input from various scientific areas.

However, the main research approach was testing of risk analysis methods and the development of frameworks for risk analysis. The following methods were used in the work:

- Bayesian networks,
- Bow-tie models (Fault tree and event tree analysis),
- Sensitivity analysis,
- Reliability importance indicators,
- Monte Carlo simulation,
- Life curve modelling.

The motivation for choosing the first five methods was that they are well recognised in the risk literature, and they are among the methods most often referred to. The last method, Life curve modelling, is a method which have recently been developed (Welte, 2008a) and which is being further tested for application among Norwegian distribution companies.

The methods were tested on several cases based on input from electricity distribution companies, and the results were discussed with researchers and electricity distribution professionals in various settings.

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[11] Song by John Lennon and Paul McCartney, issued on the *Let It Be* album, 1970.

2.2 THE CONTEXT OF THE WORK

The work reported in this thesis has been performed as an independent piece of work, organized as one of the work packages in the RISK DSAM project at SINTEF Energy Research. Although it was conducted independently, the work has been performed in interaction with other projects and activities at NTNU and SINTEF Energy Research.

Figure 2 gives a schematic illustration of the context in which the PhD work was performed. A brief description of the different aspects is provided in the following.

Figure 2 Schematic illustration of the context of the PhD work.

PhD work

The work has focused on the overall objective of exploring methods for risk analysis in asset management decision making. The work has been performed based on the present status of risk analysis in electricity distribution companies, collecting input from the risk literature and applications in other industrial sectors.

Other research projects

During the work there has been a mutual exchange of information between the work done in this PhD and other research activities at SINTEF Energy Research. This applies especially to the RISK DSAM project.

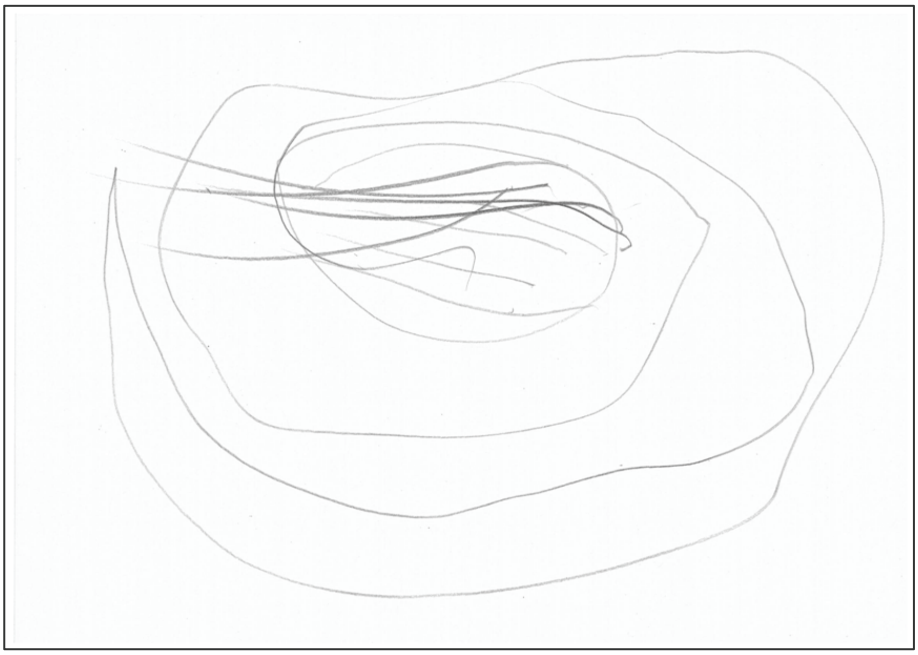
Industry experience and input
Risk management challenges have been discussed with various stakeholders both in Norwegian and international electricity distribution companies. The discussions have been useful in understanding the challenges that companies face.

Review of literature
Throughout the PhD study, input from risk literature has been sought and used to increase understanding about risk management in the electricity distribution sector as well as in other businesses and scientific disciplines.

Risk analysis methods
One important part of the work has been to explore methods for risk analysis. The methods have all been applied previously in other industrial sectors, so the work has mainly focused on the use of the methods in this new area of application.

Development of study course
Results from the PhD work have been used to develop a post-qualifying course at NTNU - *"Risk based maintenance and renewal of distribution grids"*. This has been done in cooperation with senior researcher Eivind Solvang at SINTEF Energy Research. The results from the PhD work have contributed to a structured basis for using risk analysis in electricity distribution system asset management.

Dissemination of results
Throughout the work, results have been published and presented at conferences, seminars, courses, etc. This has been done as a part of the quality assurance of the work, through getting feedback from other researchers and engineers.



“The road” – original artwork by Øystein, 3 years old.

3 ASSET MANAGEMENT

"Here, there and everywhere"[12]

This chapter provides a brief introduction to the concept of asset management, and how it applies to electricity distribution.

3.1 BACKGROUND AND DEFINITIONS

During the last 10 to 15 years, *asset management* has been adopted as the ruling paradigm for the management of electricity distribution companies (Hammond, 2000, Brown and Humphrey, 2005). The principles of asset management have been developed in industries that are heavily dependent on the performance of physical infrastructure assets – such as water supply, transportation and energy supply. The widespread application of asset management has led to the formulation and publication of the publicly available specification PAS 55 "Asset Management" (BSI, 2008a, BSI, 2008b) by the British Standards Institution. PAS 55 is being used as a guide in many electricity distribution companies throughout the world, see e.g. (Hughes, 2005, Berende et al., 2009, Pschierer-Barnfather, 2009).

The literature includes several definitions of asset management. In (Brown and Spare, 2004), asset management is somewhat poetically described as *the art of balancing cost, performance and risk*, with the further statement that asset management is a business philosophy designed to align corporate goals with asset spending decisions. In this lies the idea of making it possible to follow high-level corporate objectives down to the management of specific assets.

In (BSI, 2008a), a more formal definition of asset management is given as:

> *"Systematic and coordinated activities and practices through which an organization optimally and systematically manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational plan."*

[12] Song by John Lennon and Paul McCartney, issued on the *Revolver* album, 1966.

The two definitions state that the management of *risk* is one of three core elements of asset management, together with cost and performance. Hence, risk analysis and management will be important parts of a holistic asset management approach.

3.2 ASSET MANAGEMENT ROLES AND FRAMEWORK

As the definitions indicate, asset management covers a broad range of issues, and describes a philosophy rather than a limited process.

Asset management includes three major roles that are often referred to as:
- Asset owner,
- Asset manager,
- Service provider.

The *asset owner* is responsible for setting the overall decision criteria, the *asset manager*'s task is to translate these criteria into an asset plan, while the *service provider* executes the plan and provides feedback (Brown and Spare, 2004).

The three roles and their focal areas each address parts of the life-cycle management of the assets. The idea behind this decoupling is that each of the roles should focus on its core processes, while still contributing to one overall asset management framework, as illustrated in Figure 3.

Figure 3 Asset management framework, (Brown and Spare, 2004).

Risk analysis and management have their rightful places in several of the tasks of the framework in Figure 3, for example:

- Corporate strategy making,
- Operation planning,
- Maintenance planning,
- Project evaluation,
- Construction,
- Operation, and
- Maintenance.

All of these tasks require methods to analyse risk problems and to provide input to decision making.

The asset management framework follows a *Plan-Do-Check-Act* (PDCA) principle, known as the principle of *continual improvement*. This principle is a widely recognised way of thinking in many business disciplines, as described in e.g. (Deming, 2000 p. 23). According to (BSI, 2008a), the PDCA phases of asset management corresponds to:

- *Plan*: Establish asset management strategies, objectives and plans,
- *Do*: Implement the asset management plans,
- *Check*: Monitor and measure results,
- *Act*: Take actions to ensure that objectives are reached, and improve the asset management system.

The PDCA principle applies to all three asset management roles and the tasks in the asset management framework, with the goal of identifying improvement potentials and optimizing existing practices. This principle will also apply to the risk analysis that supports decisions in different parts of the framework.

3.3 ASSET MANAGEMENT IN ELECTRICITY DISTRIBUTION

The principles of asset management cover widely, as described in the previous sections. In the context of electricity distribution, these principles will influence tasks throughout the organisation, such as:

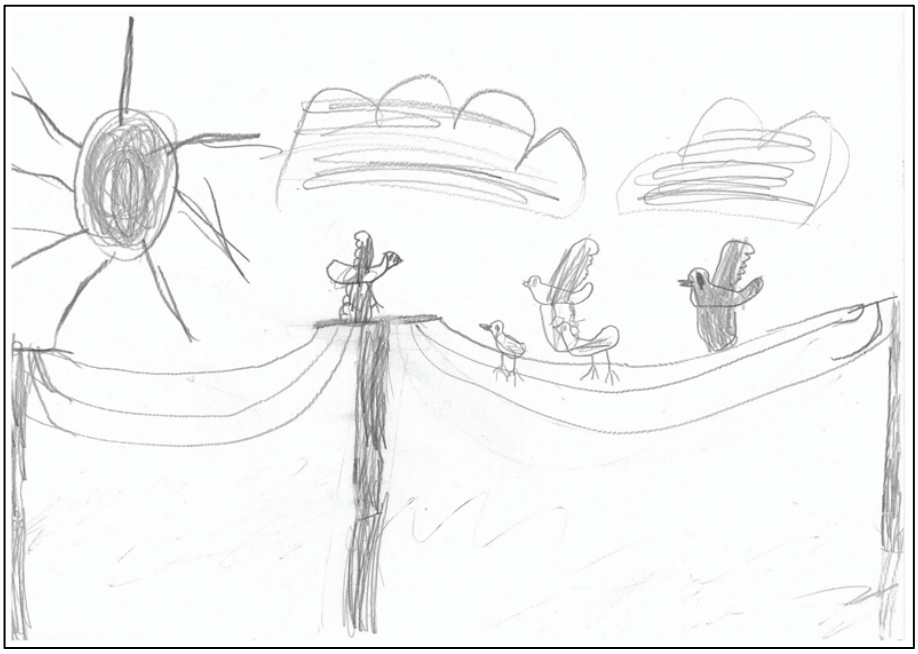
- Investment planning,
- Maintenance strategy making,
- Reinvestment planning,
- Execution of plans.

Electricity distribution companies in general face the challenge of managing an already existing – and ageing infrastructure (Nordgård et al., 2008, Sinclair, 2009).

This has led to an increased focus on maintenance and reinvestments, as these are two correlated ways of controlling the occurrence of different undesired events, and hence of controlling the distribution companies' risks.

Therefore, the challenges related to maintenance and reinvestments are high on the agenda of electricity distribution companies in many countries (Sand et al., 2007, Hughes et al., 2009, Sinclair, 2009). This has also been the foundation for the work reported in this thesis.

In the end, asset management is about making decisions to create a robust electricity distribution system, balancing cost, performance and risk. Risk analysis is hence a concept that is very suitable for the asset management toolbox.



"Power lines with birds" – original artwork by Bjørnar, 7 years old.

4 RISK AND RISK MANAGEMENT

"We can work it out"[13]

This chapter gives an introduction to risk, risk management and risk analysis in general, and how these concepts apply to electricity distribution system asset management.

4.1 RISK

Risk is related to future events and their consequences (Aven, 2008 p. 17). Risk analysis is relevant in most decision situations since by assessing risk, we seek to look into the future and to this insight to make good decisions.

The foundations of risk and risk analysis can be traced back through history, following many steps that contribute to what we today recognise as parts of risk management, see e.g. (Covello and Mumpower, 1985, Bernstein, 1996).

Even though the concept has developed over literally thousands of years, a review of different literature sources shows that there has been no convergence towards an interdisciplinary definition of *risk* – see e.g. (Kaplan, 1991, Aven and Renn, 2009). There is still an ongoing debate over how risk should be defined and about the appropriateness of the different definitions, see e.g. (Steen and Aven, 2009, Aven and Renn, 2009, Grøtan et al., 2010).

The following anecdote quoted from (Kaplan, 1997) illustrates the complexity involved in developing an interdisciplinary definition of risk:

> *"One of the first initiatives from the Society for Risk Analysis*[14] *was to establish a committee to define the word risk. The committee laboured for 4 years and then gave up, saying in its final report, that maybe it is better not to define risk and let each author define it in his own way, emphasizing that each should explain clearly what way that is."*

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[13] Song by John Lennon and Paul McCartney, issued on the *Day Tripper/We can work it out* single, 1965. *We can work it out* is the only Beatles song where a reference is made to *risk*.
[14] The *Society for Risk Analysis* is an international society that provides an open forum for all those who are interested in risk analysis, www.sra.org.

Hence, there are a number of definitions available – originating from many sources in different disciplines. A listing of selected definitions is presented in (Aven and Renn, 2009):

1. Risk equals the expected loss.
2. Risk equals the expected disutility.
3. Risk is the probability of an adverse outcome.
4. Risk is a measure of the probability and severity of adverse effects.
5. Risk is the combination of probability of an event and its consequences.
6. Risk is defined as a set of scenarios s_i, each of which has a probability p_i and a consequence c_i.
7. Risk is equal to the two-dimensional combination of events/consequences and associated uncertainties (will the events occur, what will be the consequences).
8. Risk refers to uncertainty of outcome, of actions and events.
9. Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain.
10. Risk is an uncertain consequence of an event or an activity with respect to something that humans value.

Some of the definitions are quite specific (e.g. no. 2 and 3), while others are more open in their formulation (e.g. no. 9 and 10).

Even though the debate about different definitions can be on a rather philosophical level, it is important to be aware of the potential diverging interpretations of the terms when presenting results from risk analyses.

For the purpose of the work presented in this thesis, the definitions of risk presented in (ISO/IEC, 2002)[15] and (Kaplan, 1997) were used, corresponding to no. 5 and 6 respectively in the above listing. The definitions were chosen because they are recognised as robust approaches to defining risk for engineering purposes, see e.g. (Vatn, 2006, Sand et al., 2007), and they have shown to be applicable to the risk problems that have been investigated in this work. Kaplan's definition provides a framework for how to think about risk, while the definition of ISO/IEC focuses on the applications in risk analyses. In such a context the definition of (ISO/IEC, 2002) can be seen as a subset of the definition of (Kaplan, 1997).

[15] In November 2009, (ISO, 2009) was issued to replace (ISO/IEC, 2002). The definition of risk was here changed to "*risk: effect of uncertainty on objectives*", commenting in a note that the definition from (ISO/IEC, 2002) is a definition *often used*. For the purpose of this thesis, the definition from (ISO/IEC, 2002) is still considered appropriate, and is therefore kept.

Kaplan captures the essence of "*What is the risk?*" for a given process or activity by answering a triplet of questions (Kaplan, 1997):

- What can go wrong?
- How likely is that to happen?
- If it does happen, what are the consequences?

The answers to these three questions will give a picture of the risks, where the answer to the first question is called a risk scenario that describes some kind of undesired event[16]; the answer to the second is a probability statement, while the answer to the third question is a description of potential consequences – which typically will be multi-dimensional. For example, if a specified undesired event occurs, it may have economic, reputational and safety consequences. Even though the questions may look simple, the answers still pose significant challenges with regards to risk identification, probability estimates and consequence estimates.

(ISO/IEC, 2002) provides a more narrow definition stating that *risk* is the *combination of the probability of an event and its consequence*. This is illustrated in Figure 4.

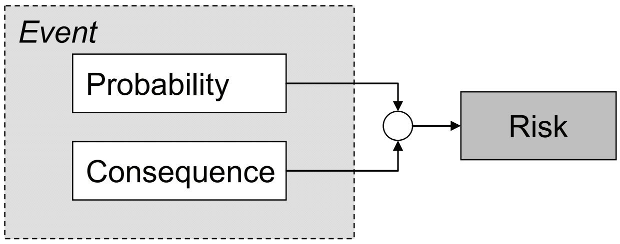

Figure 4 The relationship between *event, probability*, *consequence* and *risk* – based on (ISO/IEC, 2002).

This definition is in line with Kaplan's triplet of questions, where the event is the answer to the first question, the probability is the answer to the second, and the consequences are the answer to the third. The terminology of risk and risk management in (ISO/IEC, 2002) forms the basis for the terminology used in this thesis, as well as in the RISK DSAM project (Sand et al., 2007).

The definitions of (Kaplan, 1997) and (ISO/IEC, 2002) are broader than the often-used definition stating that *Risk equals the product of probability and consequence (of an undesired event)*, corresponding to number 1 in the listing on page 18, which presupposes that both the probability and consequence can be formulated numerically. This will often not be the case, for example when using simplified risk analyses in combination with risk matrices, see e.g. (Nordgård et al., 2007b, Nordgård and Samdal,

[16] In this thesis the term "Undesired event" is used to describe an event which answers to the question "*What can go wrong?*". *Undesirable event* (Aven 2008) and *Unwanted event* (Nordgård et.al.2005) are equivalent terms.

2010). The definitions of Kaplan and ISO/IEC allow for both a qualitative and a quantitative description of risk, and hence provide a more versatile basis for risk analysis.

For simplified risk analyses, the combination of probability and consequence terms will typically be a qualitative evaluation, while for numerical analyses using model-based methods, the combination of the probability of an undesired event and the consequences of that event, will be represented by their product or their distributions.

4.2 RISK MANAGEMENT

The literature also provides several proposed frameworks to define and describe *risk management*, emphasising different aspects to be included in the term, see e.g. (Ale et al., 2010). Some examples of risk management frameworks can be found in (ISO/IEC, 2002), (AS/NZS, 2004) and (Haimes, 2009 p. 62).

In (ISO/IEC, 2002), risk management is defined as *coordinated activities to direct and control an organization with regard to risk*, stating that risk management generally includes the sub-processes:

- Risk assessment,
- Risk treatment,
- Risk acceptance, *and,*
- Risk communication.

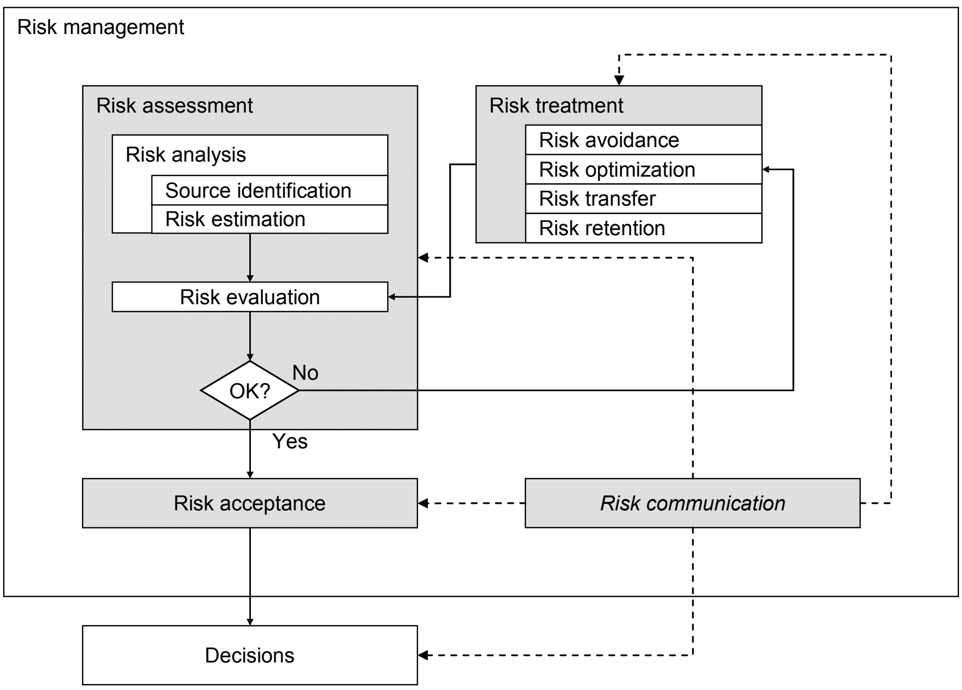

Figure 5 Risk management process – from Paper VII (Nordgård, 2008b) - based on the structure and terminology from (ISO/IEC, 2002).

For the purpose of this thesis, the structure and terminology of the risk management process from (ISO/IEC, 2002) was used, as illustrated in Figure 5. The work of this thesis has mainly focused on *risk analysis* (as a part of *risk assessment*), and *risk communication*.

4.3 METHODS FOR RISK ANALYSIS

During the last decades, numerous methods have been developed to analyse risk, see e.g. (Aven, 2008 p. 57-84) and (Rausand and Utne, 2009 p. 133-254). Three main categories of risk analysis methods are presented in (Aven, 2008 p.4) and are listed in Table 1.

The three categories represent an increasing degree of formalism and modelling sophistication, and the choice of method will depend on several factors, including the risk problem at hand, the purpose of the risk analysis, the input data that are available, etc. The need for data is significantly increased from simplified risk analyses to the model-based analyses.

There may be no single method that can address all the different dimensions of a given risk problem. For example, (Aven, 2008 p. 34) states that it can be necessary to perform several risk analyses in sequence, first performing an initial (and relatively simple) risk analysis, followed by more in-depth studies where applicable.

Table 1 Categories of methods for risk analysis – from Paper V (Nordgård et al., 2010a). Grouping based on (Aven, 2008).

Category	Type of analysis	Description	Examples of methods
Simplified risk analysis	Qualitative	Informal procedures that analyses risk using e.g. brain-storming sessions and group discussions.	- Coarse risk analyses - Brainstorming sessions
Standard risk analysis	Qualitative or quantitative	More formalized procedures in which recognized risk analysis methods are used. Risk matrices are often used to present the results.	- Risk analysis assisted by HAZOP (Hazard and operability analysis) - Risk matrices - Job safety analysis
Model-based risk analysis	Primarily quantitative	Formal methods using e.g. event tree analysis (ETA) and fault tree analysis (FTA) are used to calculate risk.	- Fault tree analysis - Event tree analysis - Reliability analyses - Bayesian networks - Electrical system simulation - Benchmarking methods

4.4 RISK ANALYSIS METHODS IN ELECTRICITY DISTRIBUTION SYSTEM ASSET MANAGEMENT

There is a trend among electricity distribution companies towards using risk analysis as one of the inputs in their asset management processes, see e.g. (Sand et al., 2007, Sinclair, 2009).

Several of the regulations that apply to the electricity distribution sector also state that risk analyses and evaluations should be performed to ensure the safe operation of the system, see e.g. (DSB, 2005 § 2.2). However, the regulations do not state how the risk analyses should be carried out.

As described in section 1.1, there are different consequence categories which are relevant for electricity distribution companies (Sand et al., 2007):

- Economic risk,
- Safety risk,
- Environmental risk,
- Quality of supply risk,
- Reputational risk,
- Vulnerability risk, and
- Regulatory risk.

All of these risks consequence categories are not applicable to every decision in the electricity distribution companies, but together the categories constitute a whole describing the different aspects of distribution company risk.

The risk consequence categories also have their differences with regards to the type of their impact. Paper V (Nordgård et al., 2010a) provides a description of three types of impacts which can be used to characterise this:

- Local impact – denoting impacts coming from dedicated components that cause "concentrated" accidents or incidents.
- System impact – denoting when failure in component(s) or sub-systems gives widespread impact affecting extensive parts of the distribution system.
- Corporate impact – denoting risks that affect the foundation for conducting business. This may be as a consequence of an earlier local or system impact, or due to an independent incident.

Paper V (Nordgård et al., 2010a) further presents an overview of risk analysis methods that are being used in the analysis of risks in Norwegian electricity distribution companies. A summary of the risk consequence categories, their predominant impacts and risk analysis methods is presented in Table 2.

Table 2 Summary of risk consequence categories, their predominant impacts and risk analysis methods – based on Paper V (Nordgård et al., 2010a).

Risk consequence categories	Risk impact			Type of risk analysis method**			Methods used
	Local	System	Corporate	Simplified	Standard	Model-based	
Economic risk			+		+	+	NPV-analyses Coarse risk analysis*
Safety risk	+		+	+	+		Brain-storming, Coarse risk analysis*
Environmental risk	+	(+)	+	+	+		Coarse risk analysis*
Quality of supply risk	+	+		+	+	+	NPV-analyses, Power system analysis
Reputational risk	+		+	+	+		Coarse risk analysis*
Vulnerability risk		+	+	+	+	+	Coarse risk analysis* Power system analysis
Regulatory risk			+		+	+	Coarse risk analysis* Simulation (e.g. data envelopment analysis)

* Coarse risk analyses are very often used in combination with risk matrices.

** The categories of risk analysis methods are listed in Table 1.

"+" indicates the relevance of the types of risk impact and risk analysis method for each consequence category. "(+)" denotes partial relevance.

Table 2 shows that type of impact and type of methods used diverge across the various consequence categories (perhaps excepting the use of coarse risk analysis, which in principle can and has been used for most categories). Due to the diversity in risk consequence categories, there is no single risk analysis method that covers all of the different risks. Different methods are hence used for different purposes, each of which constitutes a part of the total picture. This acknowledgement is also made by (Haimes, 2009 p. 194) who states that no single model can capture all the dimensions of risk assessment and risk management.

There are alternatives to this division of risk analyses, such as to monetise all the various consequence categories as discussed and exemplified in e.g. (Vatn et al., 1996, Hughes et al., 2009), and merge the inputs into a net present value (NPV) calculation. Such approaches have not been widely used by Norwegian electricity distribution companies, and have neither been investigated in this PhD work.

4.5 INTANGIBLE RISKS IN ELECTRICITY DISTRIBUTION SYSTEM ASSET MANAGEMENT

Several of the risks related to the consequence categories listed in section 4.4, are what can be called *intangible risks*. For the purpose of this thesis, intangible risk is used to denote risks whose consequences are hard to quantify in economic terms, even though it is possible to measure them in other terms. Intangible risks particularly refer to risks related to safety and environmental impact, but the term can also include reputational risk, political risks and similar.

There is an increasing awareness among electricity distribution companies on developing holistic asset management strategies covering the different relevant risk consequence categories, as described in e.g. (Nordgård et al., 2005, Nordgård et al., 2007a), and then there is a need to analyse the different risks in a structured manner – since they all constitute input to asset management decision making.

Previously, intangible risks have usually been addressed using simplified or standard risk analysis methods, see for example (Nordgård et al., 2005, Nordgård et al., 2007b, Nordgård and Samdal, 2010).

QRA methods have not been widely applied for analysing intangible risks in electricity distribution systems. Only a few applications have been found in the literature, see (Houbaer and Seddon, 1995, Hamoud et al., 2006, Hamoud et al., 2007).

Houbaer and Seddon report on the application of fault tree and event tree analysis to calculate expected frequencies for flashover hazard (reflecting safety risk) for transmission line spans. Hamoud et al. report in the two references on quantifying safety risks associated with the catastrophic failures of transmission station or substation equipment, through estimating a safety index representing the frequency of occurrence of potential safety incidents.

This PhD work has focused on the quantitative analysis of intangible risks, with the aim to provide decision support in electricity distribution system asset management.

5 MAIN RESULTS FROM THE WORK

"Come together"[17]

This chapter presents the main results of the work, divided into the work's six sub-objectives.

As described in section 1.2, the main objective for the PhD work was to explore risk analysis methods which can be used to support decision making in electricity distribution system asset management, emphasising on the analysis of intangible risks. This objective was further elaborated into the following six sub-objectives:

1. Describe the basic concepts of risk and risk management.
2. Elaborate on challenges related to risk communication and perception.
3. Test and evaluate methods for quantitative risk analysis for distribution system asset management decision support, focusing on bow-tie models and Bayesian networks. Included in this is to explore uncertainty in risk analysis.
4. Elaborate on challenges and possible solutions related to acquiring numerical input data for quantitative risk analyses.
5. Establish a framework for risk-informed decision making in distribution system asset management, emphasising the use of risk analysis, *and:*
6. Test and exemplify results from the above stated sub-objectives, through realistic cases.

Each of these sub-objectives is addressed in the following sections. Most of the results from the work are documented in the papers included in *Part II - Papers*, but to support the understanding and readability of this chapter, excerpts of examples from some of the papers are included.

[17] Song by John Lennon and Paul McCartney, issued on the *Abbey Road* album, 1969.

5.1 THE CONCEPTS OF RISK

The results corresponding to this sub-objective are to a large degree described in Chapter 4. Therefore only a brief description is given here.

In order to use risk analysis in asset management decision support, it is necessary to explore some of the basic concepts of risk.

This part of the work was mainly conducted through a review of different literature sources. There is relatively little to be found in the electrical engineering literature concerning this topic, and hence the relevant sources have been found in the general risk literature.

The main findings concerning this sub-objective are mainly presented in Chapter 4, as it has its natural place as part of the background description for the work. The sub-objective is also briefly treated in Paper VI (Nordgård, 2009b) and Paper VII (Nordgård, 2008b).

The following results summarise the work related to this sub-objective:

- There is no convergence in the risk literature on an interdisciplinary definition of *risk*, and there is still an ongoing debate as to how risk should be defined and what should be included in risk management concepts.
- For the purposes of the work presented in this thesis, the definitions of risk that are presented in (Kaplan, 1997) and in (ISO/IEC, 2002) have shown to provide a sufficient foundation for risk analysis in electricity distribution asset management. Kaplan's definition provides a framework for how to think about risk, while the definition of ISO/IEC applies more specifically to the analysis of risk.
- There are several frameworks that describe risk management. The framework based on (ISO/IEC, 2002) was used for the purposes of this thesis. This framework has proven suitable for the work, specifically through highlighting that risk communication has a significant part in the concept of risk management.

5.2 RISK PERCEPTION AND COMMUNICATION

As stated in the risk management framework in (ISO/IEC, 2002), illustrated in section 4.2, risk communication plays an important role within risk management as a whole. A lot of research has been done within this topic (as outlined in e.g. (Drottz-Sjöberg, 2003), but little has been done with regards to application within the electricity distribution sector.

The aim of this part of the work has been to examine the aspects of risk communication that have relevance to electricity distribution system asset management. Paper VII (Nordgård, 2008b) describes the main findings concerning this sub-objective.

The topic is – at a minimum – twofold, and involves:

- The terminology of risk (described in section 5.2.1).
- Aspects influencing stakeholders' perception of risks (described in section 5.2.2).

5.2.1 The terminology of risk

As described in section 4.1 and 5.1, there are a number of definitions of risk available in the literature.

Differences in risk terminology can therefore pose a challenge when communicating risk analysis results, as described in Paper VII (Nordgård, 2008b). It is important to be aware of this, and particularly to try to avoid terminology problems by clearly stating what is meant by the different terms when performing and documenting risk analyses (Sand et al., 2007 p. 11-16).

5.2.2 The perception and acceptability of risk

Risk perception is the judgement that stakeholders make about the characteristics and severity of a given risk, and their perception of risk will further influence the way they act on risk information. The acceptability of a given risk lies in the "eyes of the beholder", and is therefore dependant on the stakeholder, see e.g. (Slovic, 1998, Starr, 1969, Fischhoff et al., 1981 p. 134-140). Hence, what one stakeholder finds to be acceptable risk can be unacceptable for another.

There are several aspects that influence stakeholders' perception of risks. The pioneering work of Chauncey Starr (Starr, 1969) points out two main aspects; the first is the *voluntariness* of being exposed to a risk, and the second is the *benefits* that are perceived from the risk exposure. Fundamentally, it is much easier to accept risk that is of your own choosing, rather than risk which you feel is forced on you. It is also much easier to accept a risk from which you benefit yourself.

(Covello and Sandman, 2001) provide a comprehensive summary of aspects that influence stakeholders' perception of risk. Excerpts from this listing are presented in Paper VII (Nordgård, 2008b), with key points presented in Table 3.

Table 3 Aspects affecting stakeholders' perception of risk.
Excerpts from (Covello and Sandman, 2001).

Risk aspect	Description
Voluntariness	Risks from activities considered to be involuntary or imposed (e.g., exposure to chemicals from an industrial facility) are judged to be greater, and are therefore less readily accepted, than risks from activities that are seen to be voluntary (e.g., smoking or sunbathing).
Controllability	Risks from activities viewed as under the control of others (e.g., releases of toxic chemicals by industrial facilities) are judged to be greater, and are less readily accepted, than those from activities that appear to be under the control of the individual (e.g. driving a car).
Familiarity	Risks from activities viewed as unfamiliar (e.g. chemicals or radiation from waste disposal sites) are judged to be greater than risks from activities viewed as familiar (such as household work).
Benefits	Risks from activities that seem to have unclear, questionable, or diffuse personal or economic benefits (e.g. waste disposal facilities) are judged to be greater than risks from activities that have clear benefits (jobs, monetary benefits, automobile driving).
Catastrophic potential	Risks from activities viewed as having the potential to cause a significant number of deaths and injuries grouped in time and space (e.g., airplane accidents) are judged to be greater than risks from activities that cause deaths and injuries that are scattered or random in time and space (e.g. automobile accidents).
Uncertainty	Risks from activities that are relatively unknown or that pose uncertain risks (e.g., risks from genetic engineering) are judged to be greater than risks from activities that appear to be well known to science (e.g. actuarial risk data related to automobile accidents).
Effects on children	Risks from activities that appear to put children specifically at risk (e.g., milk contaminated with toxic chemicals, pregnant women exposed to radiation or toxic chemicals) are judged to be greater than risks from activities that do not (e.g. workplace accidents).
Trust	Risks associated with institutions or organizations lacking in trust and credibility (e.g. industries with poor environmental track records) are judged to be greater than risks from activities associated with those that are trustworthy and credible.
Media attention	Risks from activities that receive considerable media coverage (e.g. accidents at nuclear power plants) are judged to be greater than risks from activities that receive little attention (e.g., on-the-job accidents).

It is important also in electricity distribution asset management to be aware of the mechanisms that affect how people perceive risk, and that attention should also be paid to these non-technical aspects of risk management.

The perception of risk will not be static, and can change through building of knowledge and better problem understanding. In this setting the results from risk analyses can play an important part.

There are several stakeholder interfaces where risk communication is of significance in distribution system asset management, as illustrated in Figure 6. Examples of risk problems that may be relevant for these stakeholder interfaces are described in Paper VII (Nordgård, 2008b).

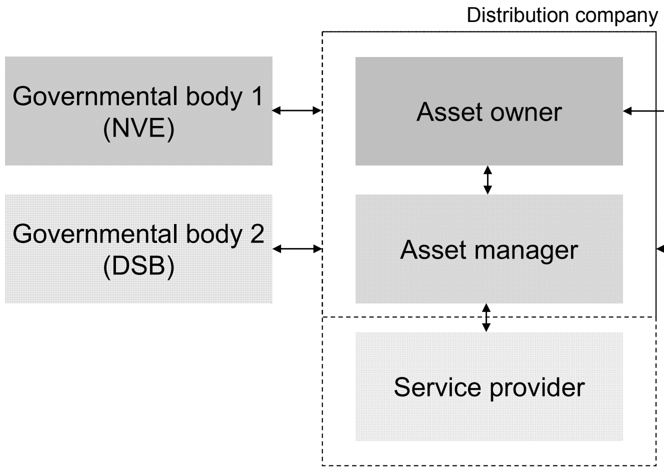

Figure 6 Schematic mapping of internal and external stakeholders and stakeholder interfaces - from Paper VII (Nordgård, 2008b).

The following results summarise the work related to this sub-objective:

- Diverging risk terminology can pose a challenge when communicating risk. It is important to be aware of this, and try to avoid terminology problems by clearly stating what is meant by different terms when risk analyses are performed and documented.
- The acceptability of a given risk lies in the "eyes of the beholder", and is therefore stakeholder dependant. It is hence impossible to objectively state what is *acceptable risk*.
- In distribution system asset management, there are several stakeholder interfaces where risk communication is of significance. Due to the different viewpoints of stakeholders, it is likely that there will be differences in how risks are perceived.

5.3 QUANTITATIVE RISK ANALYSIS METHODS USED FOR DECISION SUPPORT

One major part of the work presented in this thesis was to explore methods for quantitative risk analysis (QRA) to support decisions in electricity distribution system asset management.

In the work regarding this sub-objective, two types of QRA methods were tested:

- Bayesian networks, and
- Bow-tie models (that combine fault tree and event tree analysis).

The motivation for choosing these methods was that they are well recognised in the risk literature, and they are among the methods most often referred to, see e.g. (Rausand and Utne, 2009 p. 171-204, Aven, 2008 p. 57-84). The two methods have also been used for risk analysis in many different settings, see for example (Trucco et al., 2009, Antão et al., 2009) (Bayesian networks), and (Vatn et al., 1996, Vatn, 2006) (Bow-tie models).

There are obviously other risk analysis methods available, but due to the fact that they not as widely used and that they often are developed aiming at more specialised applications, they have not been further pursued in this work.

The following sub-sections describe what was done in this work with regards to:

- Bayesian networks (described in section 5.3.1),
- Bow-tie models (described in section 5.3.2),
- Exploring uncertainty in input data for quantitative risk analysis (described in section 5.3.3).

The results from the work related to this sub-objective are summarised in section 5.3.4.

5.3.1 Bayesian networks

The work regarding Bayesian networks is presented in Paper I (Nordgård and Sand, 2009). In this section, the application of Bayesian networks is exemplified using excerpts from the case described in this paper.

A Bayesian network is a modelling framework that has been used in many applications, such as in diagnostic systems and general reliability modelling (Langseth, 2007, Kjærulff and Madsen, 2008).

Bayesian networks offer a compact presentation of the interactions in a stochastic system by visualizing system state variables and their dependencies. It has therefore been of interest to test the usefulness of Bayesian networks to model and analyse risk problems in electricity distribution system asset management, as described in Paper I (Nordgård and Sand, 2009).

A Bayesian network consists of a qualitative and a quantitative part. The qualitative part is a directed acyclic graph where the nodes mirror the random variables and the edges of the graph represent the conditional dependence between variables. The quantitative part is a set of conditional probability functions, stating the relations between the nodes. Some basic properties of Bayesian networks are illustrated in the following example.

Example: Simple illustration of Bayesian network
Figure 7 presents a simple example of a Bayesian network[18] that models the decision as to whether to change to winter tyres on a bicycle.

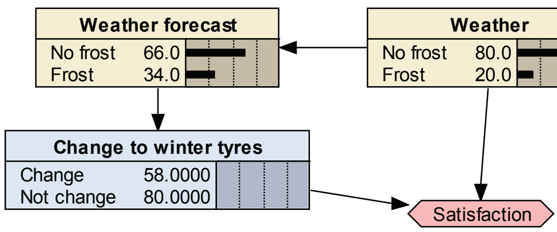

Figure 7 Example of a Bayesian network for deciding whether to change to winter tyres.

The network has two nature nodes representing the weather forecast in the evening for the coming morning (*No frost* or *Frost*) and the actual weather in the morning (*No frost*

[18] Bayesian networks containing decision nodes and / or utility nodes are also referred to as *Influence diagrams* or *Decision networks*. For the purpose of this thesis *Bayesian networks* are used, regardless of the presence of such nodes or not.

or *frost*). It has a decision node as to whether or not change to winter tyres, and a utility node that represents the decision maker's level of satisfaction.

There is a link from *Weather* to *Weather forecast*, which captures the correlation that is presumed to exist between the two. There is also a link from *Weather forecast* to *Change to winter tyres* indicating that the decision maker will know the forecast when making the decision, but no link from *Weather* to *Change to winter tyres*; since if the decision maker knew for certain how the weather was going to be, it would be easy to decide whether or not to change tyres. *Weather* is hence said to be a *parent node* to both *Weather forecast* and *Change to winter tyres*. Figure 8 shows how conditional probability tables were modelled for this case.

Weather	**Weather forecast**	
	No frost	**Frost**
No frost	80.0	20.0
Frost	10.0	90.0

Weather forecast	**Change to winter tyres**	
	Change	**Not change**
No frost	10.0	90.0
Frost	90.0	10.0

Weather	**Change to winter tyres**	**Satisfaction**
No frost	Change	50
No frost	Not change	100
Frost	Change	90
Frost	Not change	0

Figure 8 Probability assumptions used in the example modelling.

There are also links from *Weather* and *Change to winter tyres* to *Satisfaction*, capturing the idea that the bicyclist is most happy when there is no frost and he or she doesn't change to winter tyres (*utility = 100*). The next most satisfying situation is when there is a frost and he or she has changed tyres (*utility = 90*). The bicyclist dislikes using winter tyres when there is no frost (*utility = 50*), but feels the least satisfaction (and most danger...) if there is frost and the bike still has summer tyres (*utility = 0*).

Figure 7 shows that with the basic assumptions for the weather (80 % chance of no frost, 20 % chance of frost), the satisfaction is highest for not changing to winter tyres. But if the model is updated, stating that the weather forecast says it will be frost, then the largest satisfaction is for changing, as shown in Figure 9.

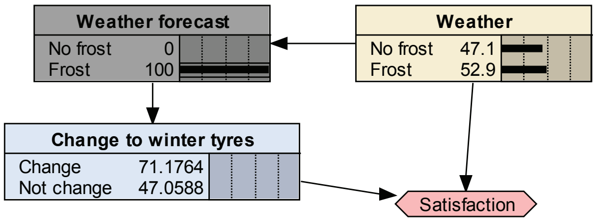

Figure 9 Updated model with weather forecast *Frost*.

End of example.

A summary of the case from Paper I (Nordgård and Sand, 2009) is presented in the following. A more detailed description of the modelling can be found in the paper. The Bayesian network software tool Netica[19] was used to model the case.

5.3.1.1 Case: Analysis of safety risk concerning air-insulated switches

In Paper I (Nordgård and Sand, 2009), a Bayesian network was used to model a safety risk problem related to 12 kV air-insulated switches in MV/LV substations. The switches have been identified as a safety risk due to the hazard related to the uncontrolled burning of an electric arc if the switch does not work as intended. The safety risk was identified in a qualitative risk screening, described in (Nordgård et al., 2005).

The main factor contributing to the uncontrolled burning of an electric arc is considered to be *slow switch operation*. A Bayesian network was established to model this case, as shown in Figure 10. The network contains 11 different nodes altogether, of which 6 have conditional probability tables that are functions of their parent nodes.

Bayesian network model

The following factors have been identified by company experts as relevant for modelling the risk related to the switches (the node numbering refers to Figure 10):

- Age of switch *(node I),*
- Operating environment *(node II),*
- Maintenance interval *(node III),*
- Encapsulation of the switch *(node IV),*
- The use of protective clothing *(node V)*.

Two states were identified as being critical with regards to the correct operation of the switch:

- If the switch poles are stuck *(node VI),* and
- If the operating mechanism moves slowly *(node VII)*.

[19] Information about Netica can be found on the producer's homepage www.norsys.com.

The maintenance action *functional control* was modelled to affect both of these states, and the time interval between these functional controls was modelled as a decision node in the network *(node III)*.

To establish a mathematical representation of the Bayesian network, conditional probability functions were formulated for each of the nodes that have parent nodes.

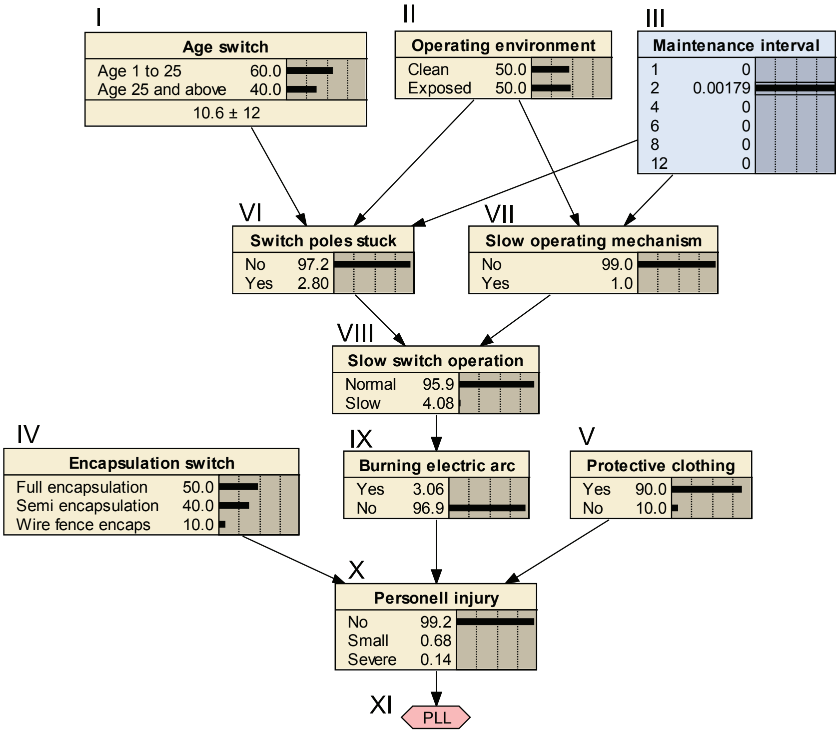

Figure 10 Bayesian network for a safety risk model for air-insulated switches – based on a figure from Paper I (Nordgård and Sand, 2009).

Input data

When analysing intangible risks, experience shows that it is hard to find statistical data which can support the choice of model parameters. The input to the case is therefore provided through discussions with distribution company experts.

The switch age was divided into two classes; *up to 25 years* and *25 years and above*. The operating environment was also split into two classes, *clean* and *exposed* environment. These modelling choices were made based on discussions with distribution company experts (Nordgård et al., 2005).

It was further assumed that a switch aged 25 years or older had a failure rate that was twice the failure rate of newer switches, while a switch operating in a clean environment was assumed to have a failure rate 1/3 the failure rate of a switch in an exposed environment. The base failure rate, λ_{pole} (for a switch younger than 25 years, operating in a clean environment), was assumed to be 0.01.

To estimate the unavailability of the switch poles, q_{pole}, i.e. the probability that the switch poles are stuck, the following equation was used (based on (Vatn, 1997)):

$$q_{pole} = \frac{\lambda_{pole} \cdot \tau_m}{2} \quad (1)$$

where τ_m is the maintenance interval in years.

Figure 11 illustrates how the availability of the switch poles, $p_{pole} = 1 - q_{pole}$, varies for different combinations of the input parameters *operating environment*, *switch age* and *maintenance interval.*

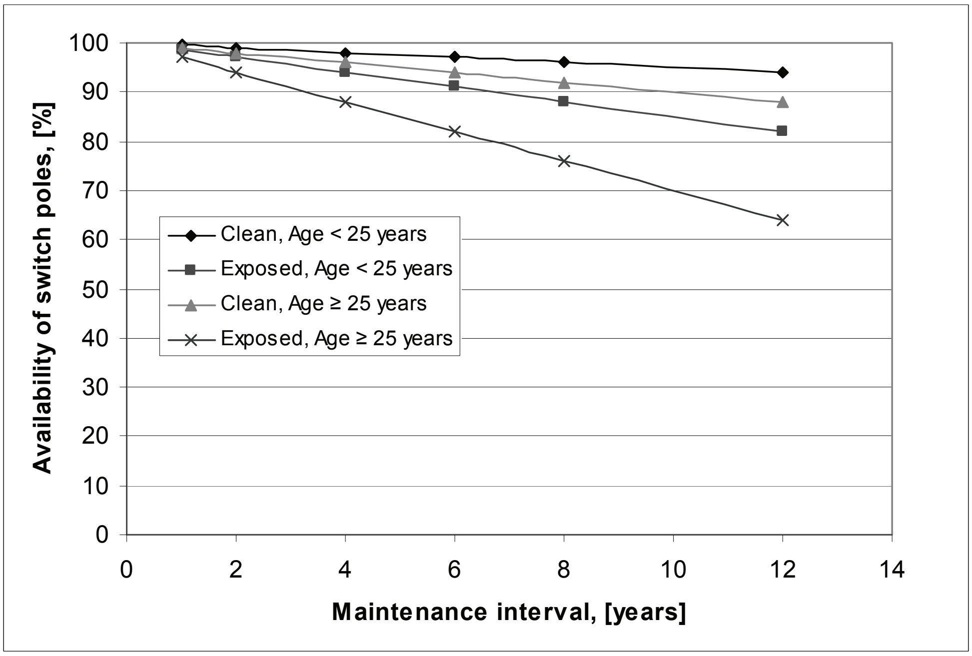

Figure 11 Availability of switch poles as function of maintenance interval for different alternatives – from Paper I (Nordgård and Sand, 2009).

The curves from Figure 11 were transferred to a conditional probability table (CPT), as shown in Table 4. The CPT was used as an input to the Bayesian network modelling.

Other CPTs were similarly established for the remaining nodes with parent nodes in the Bayesian network. This is explained in more detail in Paper I.

Barriers

Three encapsulations were considered in this case, as indicated in *node IV* in Figure 10:

- Full encapsulation,
- Semi encapsulation,
- Wire fence encapsulation.

Table 4 Example: Conditional probability table for the node *Switch poles stuck.*

Maintenance interval [years]	Age switch	Operating environment	Switch poles stuck	
			No	Yes
1	< 25 years	Clean	99.5	0.5
1	< 25 years	Exposed	98.5	1.5
1	≥ 25 years	Clean	99.0	1.0
1	≥ 25 years	Exposed	97.0	3.0
2	< 25 years	Clean	99.0	1.0
2	< 25 years	Exposed	97.0	3.0
2	≥ 25 years	Clean	98.0	2.0
2	≥ 25 years	Exposed	94.0	6.0
4	< 25 years	Clean	98.0	2.0
4	< 25 years	Exposed	94.0	6.0
4	≥ 25 years	Clean	96.0	4.0
4	≥ 25 years	Exposed	88.0	12.0
6	< 25 years	Clean	97.0	3.0
6	< 25 years	Exposed	91.0	9.0
6	≥ 25 years	Clean	94.0	6.0
6	≥ 25 years	Exposed	82.0	18.0
8	< 25 years	Clean	96.0	4.0
8	< 25 years	Exposed	88.0	12.0
8	≥ 25 years	Clean	92.0	8.0
8	≥ 25 years	Exposed	76.0	24.0
12	< 25 years	Clean	94.0	6.0
12	< 25 years	Exposed	82.0	18.0
12	≥ 25 years	Clean	88.0	12.0
12	≥ 25 years	Exposed	64.0	36.0

The reason for the different encapsulations is that the substations have been built over quite a long time period, during which technical approaches have improved, from the wire fence to the full encapsulation.

The use of protective clothing was also included as an additional barrier in the analysis, assuming that in 90 % of the cases protective clothing was used by the operator.

Safety risk

To aggregate the impact of injuries into a single safety risk measure, the concept of *Potential Loss of Life* (PLL) was used to weight the severity of the various types of injuries (Jonkman et al., 2003). The following weights were applied in the model:

- No injury, PLL = 0
- Small injury, PLL = 0.1
- Severe injury, PLL = 0.8

Based on the established Bayesian network model, different factors' influence on the safety risk were estimated (measured in *E(PLL)*).

This is illustrated in Figure 12, which shows the following:

- The safety risk was estimated to be approximately 20 times higher for the switches in the wire fence encapsulations compared to the full encapsulation.
- The doubling of maintenance intervals less than doubles the estimated PLL.
- Significantly larger maintenance intervals can be used for the fully or semi encapsulated switches as compared to the wire fence ones, while still achieving the same level of risk.

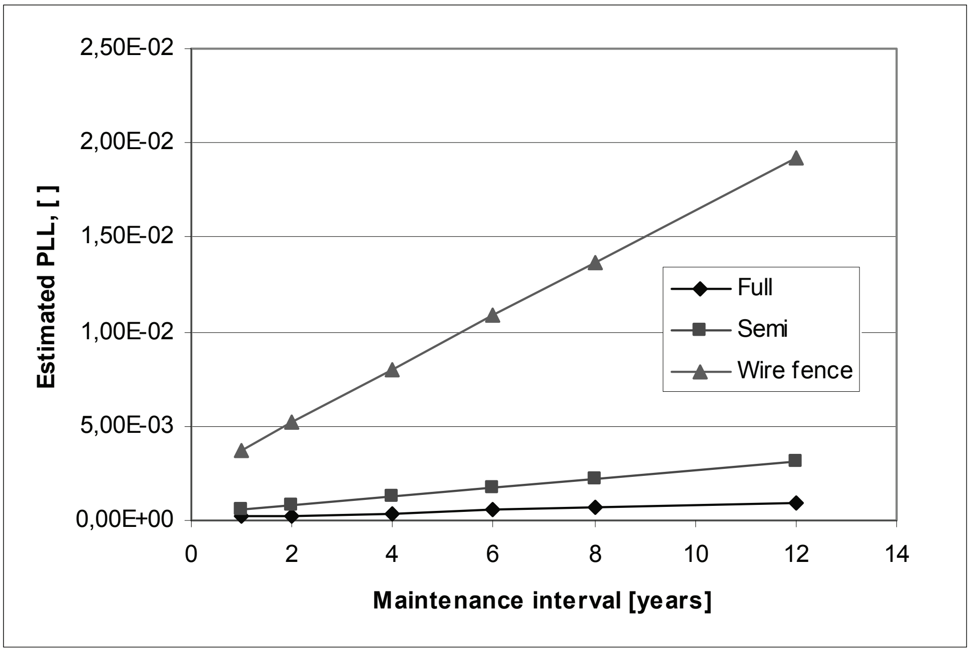

Figure 12 Estimated PLL for three different encapsulations as function of maintenance interval – from Paper I (Nordgård and Sand, 2009).

The quantitative safety risk analysis model established in the Bayesian network can be used to increase the experts' understanding of the problem and to see how their input data result in estimated PLL for the alternative configurations.

It should however be emphasised that the absolute value of PLL should be used with caution, since there are few results or data to calibrate the model against. The results for different alternatives will however give comparable results that can be used to quantify the differences between alternatives.

5.3.2 Bow-tie models

The work on the application of bow-tie models is mainly presented in Paper II (Nordgård, 2010), Paper III (Nordgård, 2010) and Paper IV (Nordgård et al., 2010b). This section expands on the use of bow-tie models using excerpts from a case in Paper III (Nordgård, 2010).

A bow-tie model is a risk analysis model that explicitly establishes cause / effect relationships for an undesired event, see e.g. (Vatn et al., 1996, Vatn, 2006 p. 14).

In this thesis, the cause analysis was performed using fault tree analysis (FTA), and the effect analysis was performed using event tree analysis (ETA). Spreadsheet models were used to perform the FTA and ETA calculations.

A conceptual bow-tie model is illustrated in Figure 13. B_i represents basic initiating events in the fault tree analysis, which lead to an undesired event through a sequence of logical gates. S_k represents different barriers, or other statements of potential outcomes, while C_j represents possible end event consequences resulting from the event tree analysis. C_Σ is the aggregation of the consequences of all end events into a common risk measure.

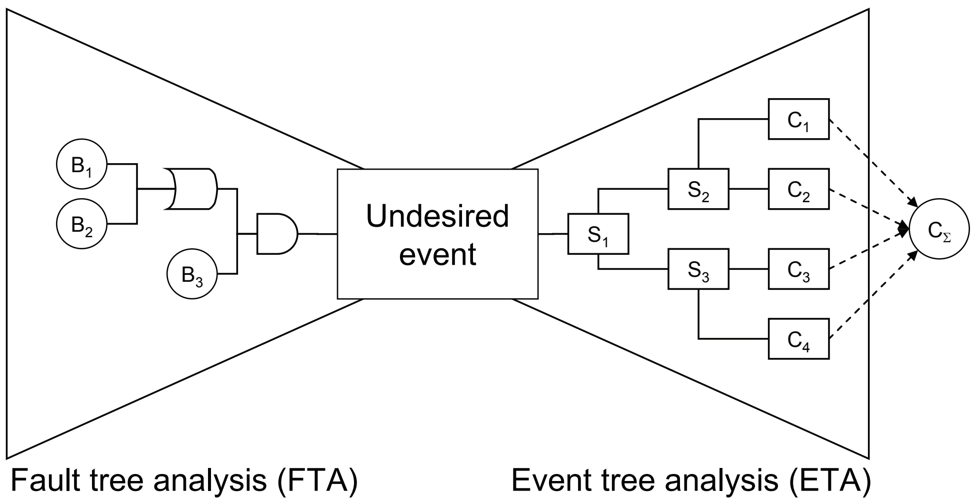

Figure 13 Conceptual bow-tie model – from Paper II (Nordgård, 2009a).

A summary of the example from Paper III (Nordgård, 2010) is presented in the following. *A similar application of a bow-tie model is also given in Paper II, but since Paper III also deals with the inclusion of uncertainty – which is treated in section 5.3.3 – the case from Paper III has been chosen to exemplify the bow-tie model. A more detailed description of the modelling can be found in the paper.*

5.3.2.1 Case: Analysis of potential oil spill from transformers

The case is based on a quantitative risk assessment model established in (Nordgård and Solum, 2009), and further described in Paper III (Nordgård, 2010). The case evaluates risk related to potential oil spills from MV/LV distribution transformers located in the drainage basin of a drinking water reservoir.

Fault tree analysis

Two main failure modes were identified through discussions with company experts:

- Oil spill due to degradation of the transformer casing,
- Oil spill due to lightning strikes destroying the transformer.

These two failure modes were modelled in a fault tree as shown in Figure 14, contributing to the top event "*Oil spill from transformer*".

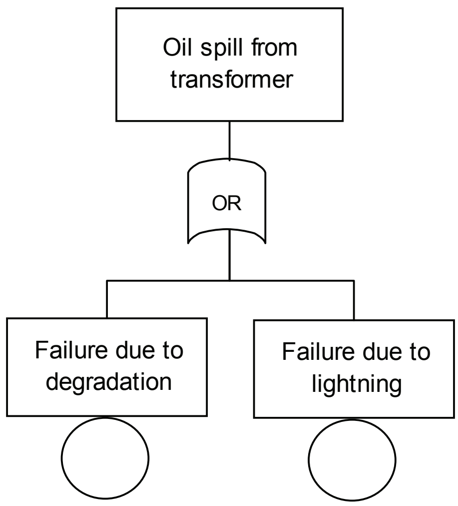

Figure 14 Fault tree - *Oil spill from transformer* - from Paper III (Nordgård, 2010).

The following information was provided by distribution company experts:

- Approximately 1 - 5 out of 1500 transformers have a leakage due to degradation each year.
- Approximately 2 – 3 out of 1500 transformers experience breakage due to lightning strikes each year.

Based on this information, the following estimates were chosen for the fault tree parameters:

- $q_{Degradation} = 2.0 \cdot 10^{-3}$ [events/year]
- $q_{Lightning} = 1.5 \cdot 10^{-3}$ [events/year]

where $q_{Degradation}$ and $q_{Lightning}$ expresses the probabilities for leakage due to casing degradation and lightning strikes respectively.

The probability of occurrence for the top event is computed according to equation (2):

$$q_{Oil\ spill} = q_{Degradation} + q_{Lightning} - q_{Degradation} \cdot q_{Lightning} \quad (2)$$

With the above stated input data, this gives $q_{Oil\ spill}$ = 0.0035. If a distribution company has 25 transformers in a drinking water drainage basin, this gives 0.0875 occurrences of the top event per year – i.e. one can expect the event to occur on average every 11 years.

Event tree analysis

In order to establish the event tree shown in Figure 15, the following barriers were considered:

- Whether an oil collector is present,
- Whether less than 10 litres of oil leaks,
- Whether the transformer is located near a waterway (stream or river) leading directly to the drinking water reservoir.

The amount of oil spilled cannot be considered to be an ordinary barrier, but rather a statement of a possible outcome.

The following numerical estimates were chosen for these barriers:

- $q_{Oil\ collector}$ = 0.9, i.e. only 10 % of the transformers in the area have oil collectors
- $q_{< 10\ liters}$ = 0.8, i.e. in only 20 % of the cases is the oil spill less than 10 litres
- $q_{Far\ from\ waterway}$ = 0.6, i.e. 60 % of the transformers are located near a stream or river leading directly into the drinking water reservoir.

The background for choosing these probability estimates was input from distribution company experts.

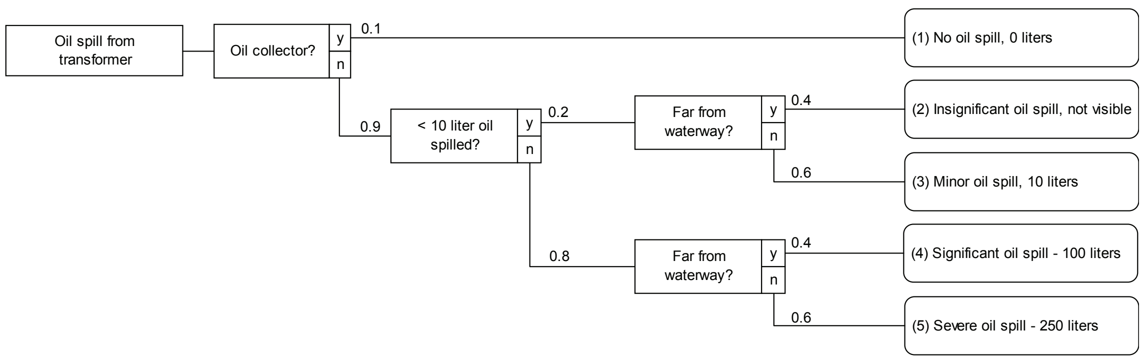

Figure 15 Event tree model for possible outcomes following the start event *Oil spill from transformer* - from Paper III (Nordgård, 2010).

The results presented in Table 5 were obtained based on the fault tree analysis, the structure of the event tree in Figure 15 and the probability estimates for the barriers.

Table 5 Results from the event tree analysis - from Paper III (Nordgård, 2010).

End event	**1**	**2**	**3**	**4**	**5**	**Sum**
Oil spill[1)]	0	1	10	100	250	-
Frequency[2)]	0.009	0.006	0.009	0.025	0.038	-
Time[3)]	114	159	106	40	26	-
E(oil spill)[4)]	0.0	0.0	0.1	2.5	9.5	*12.1*

1) Estimated oil spill of the end event, [Litres].
2) Frequency of occurrence of end event *I* [$year^{-1}$]
3) Expected time between occurrences [years]
4) Expected annual contribution to oil spill from end event *i* [Litres]

The results in Table 5 show that the total expected oil spill is estimated to be 12.1 litres/year. The most critical end event (End event 5) – with an oil spill of 250 litres – will occur on average every 26 years.

To judge whether this potential oil emission is acceptable or not, is also for the decision maker to evaluate. In Paper III (Nordgård, 2010), the results were compared to a taxonomy proposed in (Wessberg et al., 2008), evaluating the risk according to five probability categories and three consequence categories, as illustrated in Table 6.

Table 6 Risk categorisation - from Paper III (Nordgård, 2010), based on (Wessberg et al., 2008).

	Moderate	Extensive	Serious
5 - More than once a month	II	I	I
4 - More than once a year	II	I	I
3 - More than once in 10 years	III	II	I
2 - Once in a lifetime[1)]	IV	III	II
1 - Situation is known[2)]	IV	IV	IV

[1)] The lifetime of the industrial site. [2)] It has happened sometimes somewhere.

Risk categories I: Risk elimination actions must be started immediately.
II: Risk reduction needed. Proposals for actions as soon as possible.
III: Proposals for actions to risk reduction should be given within a year.
IV: No actions needed.

The estimated expected consequence for this case was estimated to be in the categories *Moderate* to *Extensive*, while the probability of occurrence was estimated to be in categories *2 or 3* – resulting in a risk category estimate of category II - IV. From this, the conclusion was drawn that the risk can not be considered unconditionally acceptable, and that proposals for risk reduction should be considered.

5.3.3 Exploring uncertainty in input data for QRA

Uncertainty in decision problem data is an inherent property of risk analyses. It is therefore important to explore this when analysing risk. This can be done through investigating the "*what-ifs*" – by performing analyses where the effects of changing input parameters are investigated and evaluated.

Paper III (Nordgård, 2010) presents and examines three approaches for exploring the effects of input data uncertainty:

- Reliability importance measures,
- Sensitivity analysis,
- Monte Carlo simulations.

The approaches were chosen due to the fact that they represent recognised ways of including uncertainty in QRA, see e.g. (Rausand and Utne, 2009 p. 253), addressing the problem in different ways and requiring different computational efforts.

Reliability importance measures

Reliability importance measures can be used to provide information concerning how a risk model will behave with regards to changes in input parameters. The literature presents a variety of different types of such measures, see e.g. (Holen et al., 1988 p. 145-157, Aven, 1992 p. 113-116, Hilber, 2008 p. 20-22). Two classic measures are used in Paper III (Nordgård, 2010):

- Improvement potential, and
- Birnbaum's measure of reliability.

The improvement potential, I^A_i can be described by the following equation:

$$I_i^A = h_i - h \tag{3}$$

where h is the reliability of the system and h_i is the reliability assuming that component i is in the best state (Aven, 1992 p. 113). Hence, I^A_i expresses the systems improvement potential if element i in the risk model is replaced with a fault-free element.

The Birnbaum's measure of reliability, I^B_i, can be described by the following equation:

$$I_i^B = \frac{\partial h}{\partial p_i} \tag{4}$$

To compute I^B_i the following formula is often used:

$$I_i^B = h(1_i, p) - h(0_i, p) \tag{5}$$

where $h(\cdot_i,p) = \text{h}(p_1,p_2,\ldots,p_{i-1},\cdot, p_{i+1},\ldots,p_n)$.

I^B_i expresses the system's sensitivity with regards to changes in element *i* and is hence a measure for how small changes in *i* will affect the system (Aven, 1992 p. 114).

I^A_i and I^B_i can both provide information concerning how sensitive the analysis results are with respect to changes in input parameters and where to look for efficient ways of reducing risk.

Sensitivity analysis
Sensitivity analysis is performed using repetitive analyses to see how changes in model parameters affect the estimated risk. Through this, information can be obtained concerning the robustness of the solution.

For the purpose of the case presented in Paper III (Nordgård, 2009b), the effects of changing only one parameter at a time were assessed.

Monte Carlo simulations
In Monte Carlo simulations, input parameters are represented by probability distributions, and results are obtained through repetitive calculations sampling from these distributions. Monte Carlo simulations require larger modelling efforts compared to sensitivity analyses. In the case in Paper III (Nordgård, 2010), several input parameters were modelled using probability distributions, where expert judgments were translated into probability distributions that again were the basis for the simulations. The software *@Risk*[20] was used to perform the Monte Carlo simulations.

5.3.3.1 Case: Exploring uncertainty in input data for QRA

The various methods for exploring uncertainty are illustrated in Paper III (Nordgård, 2010). The bow-tie model used for the case is already presented in section 5.3.2, and is not repeated in this section. A description of the model and the parameters that are referred to in this section, can hence be found in section 5.3.2.

Paper III (Nordgård, 2010) elaborates on the three methods presented above. Table 7 shows the calculated improvement potentials and Birnbaum's measures for the model parameters.

[20] Information about *@Risk* can be found on http://www.palisade.com/

Table 7 Calculated reliability importance measures for the input parameters - from Paper III (Nordgård, 2010).

Model parameter	Improvement Potential, $I^A{}_i$	Birnbaum's measure, $I^B{}_i$
$q_{Degradation}$	6.9	3448.8
$q_{Lightning}$	5.2	3448.8
$q_{Oil\ collector}$	12.1	5.7
$q_{< 10\ litres}$	11.6	6.2
$q_{Far\ from\ waterway}$	5.8	4.1

The improvement potential, $I^{A,}{}_i$, is largest for the model parameter $q_{Oil\ collector}$. It should be noted, however, that the values for the improvement potential are dependent on the values chosen as the base case reference (the value of h in equation (3)).

The Birnbaum's measures, $I^{B,}{}_i$, indicate that the estimated oil spill is clearly most sensitive to the changes in the two fault tree parameters $q_{Degradation}$ and $q_{Lightning}$, but since the failure probabilities here already are very small numbers – the improvement potential is not very large.

Sensitivity analysis

Sensitivity analyses were performed for low, best and high estimates for the input parameters. The parameter estimates are shown in Table 8.

Table 8 Parameter estimates used for sensitivity analysis – values from Paper III (Nordgård, 2010).

Model parameter	Low estimate	Best estimate	High estimate
$q_{Degradation}$	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$
$q_{Lightning}$	$1.33 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.67 \cdot 10^{-3}$
$q_{Oil\ collector}$	0.85	0.9	0.95
$q_{< 10\ litres}$	0.6	0.8	1.0
$q_{Far\ from\ waterway}$	0.5	0.6	0.7

The sensitivity analyses were performed by iterative calculations where one parameter was changed at a time. The results for low, best and high parameter estimates are shown in Figure 16.

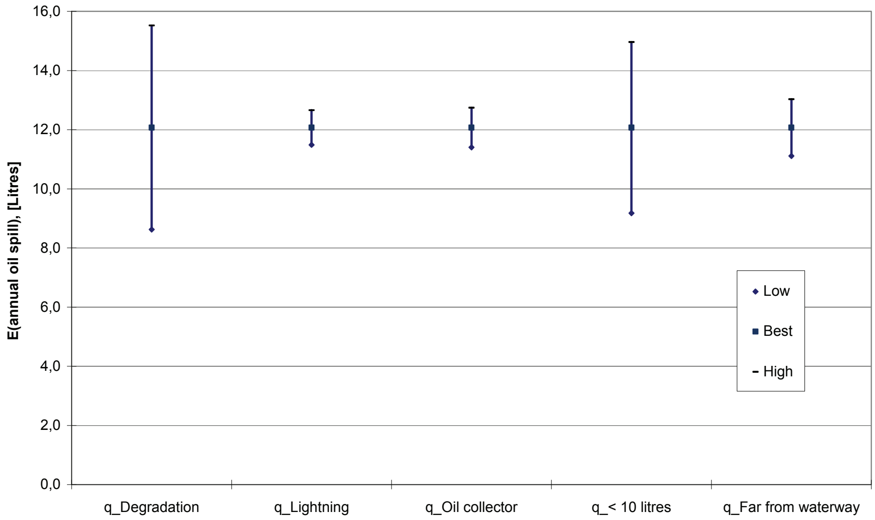

Figure 16 Variation of E(annual oil spill) for low / best / high parameter values - from Paper III (Nordgård, 2010).

Monte Carlo simulations

A Monte Carlo simulation model was established to investigate the effect of including probability distributions for the input parameters. Triangular distributions were used to represent the five input parameters listed in Table 8, with the distributions' mean values equal to the best estimates, and low and high values giving the low and high ends. The resulting distribution from a simulation of the estimated annual oil spill is shown in Figure 17.

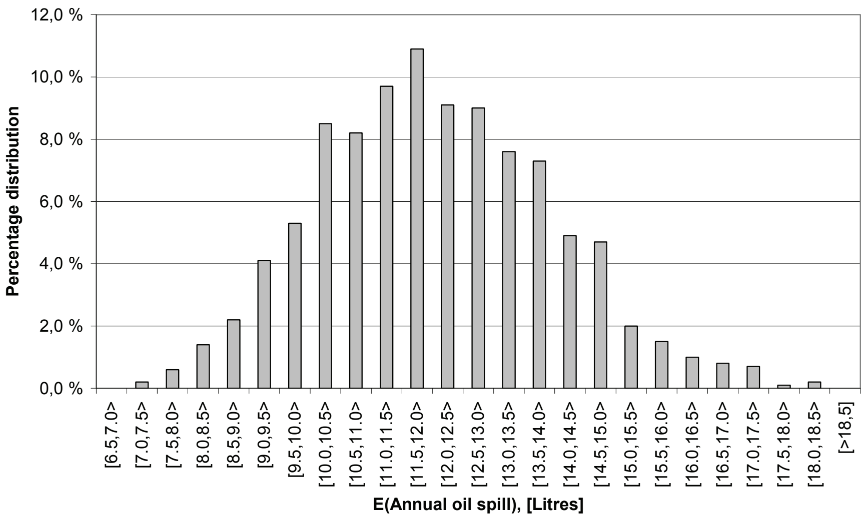

Figure 17 Monte Carlo simulation results of annual oil spill - from Paper III (Nordgård, 2010).

The Monte Carlo simulation provides a centre of gravity for the results corresponding to the expected value that was computed earlier (12.1 litres/year, see Table 5), but there is a more widespread variation of results around this value – wider than what is obtained when varying only one parameter at a time, as was done in the sensitivity analysis.

5.3.4 Summary of results

The following results summarise the work related to the third sub-objective:

- Papers I – IV illustrate that QRA methods can be applied to analyse intangible risks in asset management decision problems.
- Both Bayesian networks and bow-tie models can be used to structure and visualise risk problems, and to put the knowledge and assumptions of company experts into a structured analytical framework.
- Uncertainty is an inherent property of risk analyses, which is important to explore. Reliability importance measures, sensitivity analyses and Monte Carlo simulation are all methods capable of providing the analyst(s) and decision maker(s) with information concerning this aspect.
- QRA requires numerical inputs for various model parameters. The cases illustrate that it is hard of to find statistical data that can support the choices of such parameters. This calls for the systematic use of expert judgment as input to the risk modelling, as further described in section 5.4 and in Paper IV (Nordgård et al., 2010b).
- Compared to a simplified risk analysis, QRA will provide a better basis for comparing alternatives: however, it requires more labour. Using a combination of the methods can therefore be a practical solution – as described in section 5.5 and Paper VI (Nordgård, 2009b).

5.4 NUMERICAL INPUT DATA FOR QUANTITATIVE RISK ANALYSES

A continuing challenge with the use of quantitative risk analysis methods is acquiring data to use in the calculations. One of the sub-objectives of the work has addressed this topic.

According to (Løvås, 2004 p. 65), there are in principle three approaches for acquiring numerical data:

1. If all outcomes have the same chance of occurring, reasoning can be used to find the theoretical probabilities (For example by stating the probability of throwing 4 on a fair die).
2. Probabilities can be estimated by conducting a series of experiments and noting the relative frequency of the occurrence of an event.
3. Probabilities can be estimated expressing degrees of belief regarding the occurrence of an event.

The first approach is not considered relevant for the types of problems encountered with QRA in electricity distribution. The second approach will typically require having representative statistical material to rely on when establishing the probability estimates. The third approach requires input from people with expertise in the given field of application.

When analysing intangible risks, electricity distribution companies will rarely have relevant data that can support the use of statistical approaches to obtain data for the analysis, see e.g. (Nordgård et al., 2007b). It is therefore often necessary to rely on input from company experts to estimate the numbers used for probabilities and consequences in the analysis.

There are many possible ways for using expert judgement as input to QRA models, see e.g. (Keeney and von Winterfeldt, 1989, Clemen and Winkler, 1999).

In the work presented in this thesis, expert judgment was used in two ways:

- To provide direct estimates of failure probabilities based on expert statements, and
- To provide failure probability estimates using life curve models.

The first approach was used in Papers I-III and VI, while the latter was used in Paper IV, (Nordgård et al., 2010b) based on the methodology presented in (Welte, 2008a), and exemplified in (Heggset et al., 2007, Welte and Skjølberg, 2009).

The main reason for exploring the use of life curve models was that the method has proven to be valid for hydropower production components (Welte, 2008a), and is in the process of being tested for its usefulness for distribution system components through an ongoing project supported by Norwegian distribution companies[21], see e.g. (Welte and Skjølberg, 2009).

5.4.1 Using direct estimates

Direct estimates were used to quantify failure rates and barrier probabilities in Papers I-III and VI, by using expert's opinion on how probable a failure was, and how well a barrier was assumed to function.

The basis for making such estimates can obviously be questioned, since there often will be significant uncertainty related to the knowledge upon which the experts rely for their judgments, see e.g. (Keeney and von Winterfeldt, 1989). But by making such estimates and using them in an analytical model, the judgments are made explicit and it is possible to discuss the inputs and results on a more transparent basis (Keeney and von Winterfeldt, 1989, Apostolakis, 2004).

The use of direct estimates shown in the papers indicates that this approach is also applicable for electricity distribution system asset management.

5.4.2 Using life curves models as an input to quantitative risk analysis

Paper IV (Nordgård et al., 2010b) presents a procedure for structured use of expert judgement as an input to QRA, through the use of life curve models.

The procedure uses expert judgment to establish life curves (Anders and Endrenyi, 2002), which in turn are used to estimate time varying failure probabilities, using a semi-Markov process to model the degradation of a component. By applying phase-type distribution theory (Neuts, 1981 p. 41-80, Welte, 2008b), the semi-Markov process is converted into an ordinary Markov process, which finally provides a model for calculating failure probabilities. The life curve model concept is illustrated in Figure 18.

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[21] The project of Energi Norge: *Tilstandskontroll og restlevetid for nettkomponenter* (*Condition monitoring and residual lifetime for electric grid components).*
http://www.energinorge.no/alle/tilstandskontroll-og-restlevetid-for-nettkomponenter-article7034-302.html

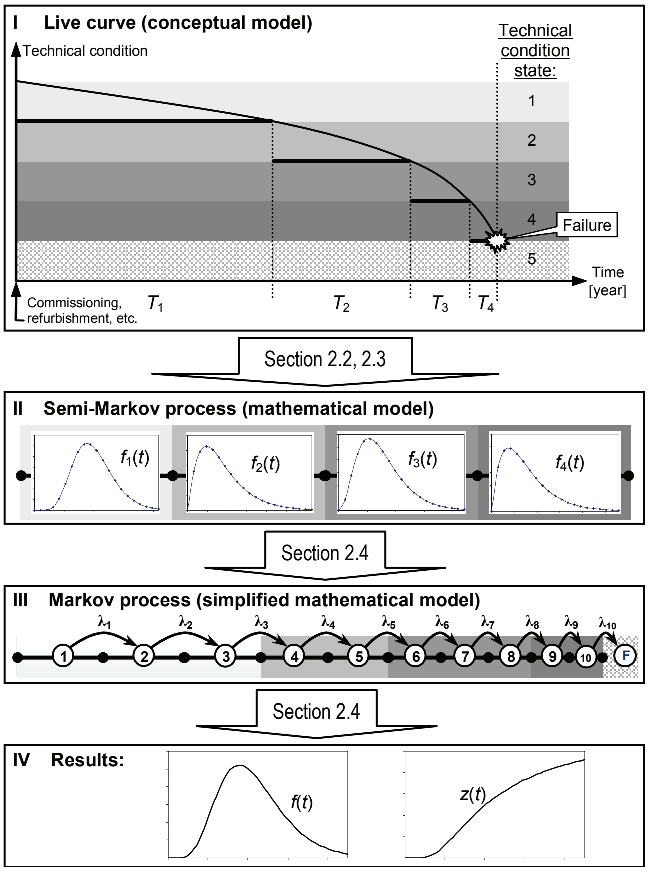

Figure 18 Concept of life curve and Markov process - from Paper IV (Nordgård et al., 2010b).

The resulting failure probabilities can be used as input to a bow-tie model, resulting in a risk measure that varies with time, as illustrated in Figure 19.

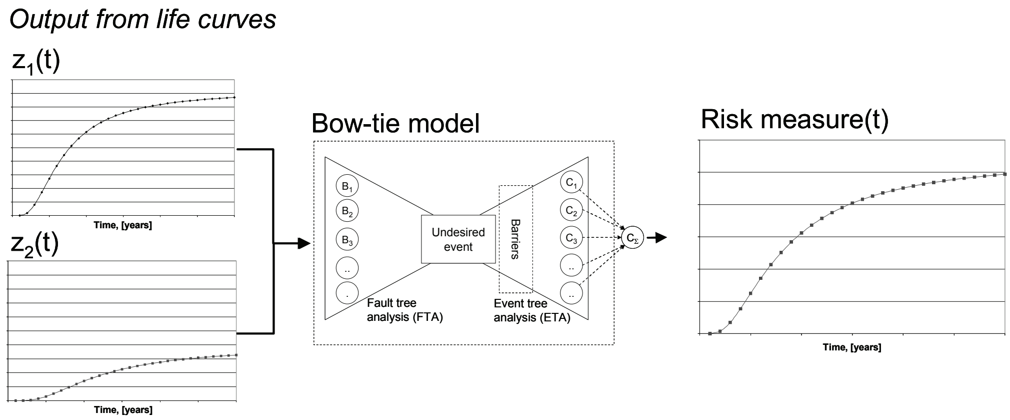

Figure 19 Conceptual model where the output from life curves is used as an input to a bow-tie model – from Paper IV (Nordgård et al., 2010b).

Paper IV (Nordgård et al., 2010b) proposes a seven-step procedure for risk-informed decision making, using life curves as an input to a QRA model:

1. Identification of the risk problem.
2. Identification of critical failure modes.
3. Establishing life curves for one or more failure mode(s).
4. Establishing a bow-tie model for quantitative risk analysis.
5. Analysing the model
6. Evaluating the risk analysis results
7. Making the decision

The procedure was applied to a case that analysed the same basic risk problem as described in Paper I (Nordgård and Sand, 2009); an analysis of safety risk related to 12 kV air-insulated switches.

Even though this case was based on the same risk problem as in Paper I (Nordgård and Sand, 2009), the analyses were performed using different input data and different models, and therefore the results are not directly comparable. The purpose of the case in Paper IV (Nordgård et al., 2010b) was to illustrate the procedure using a realistic problem, and not to replicate the case analysed in Paper I (Nordgård and Sand, 2009).

5.4.2.1 Case: Using life curves as an input to QRA

The detailed description of the risk problem is found in Paper IV (Nordgård et al., 2010b).

Slow movement of the switch during operation is regarded to be the main reason for obtaining uncontrolled electric arcs in the switchgear. Based on a qualitative evaluation of the criticality of a set of identified failure modes, the failure mode of *Slow operation of switch* was chosen to be further analysed in the case.

A life curve model consisting of two condition states was chosen for the modelling of the risk problem, as illustrated in Figure 20. The reason why only two states were chosen for this case was that there exist no well-defined condition description available for such switch disconnectors, and that it was considered hard to observe more than two condition states in practice.

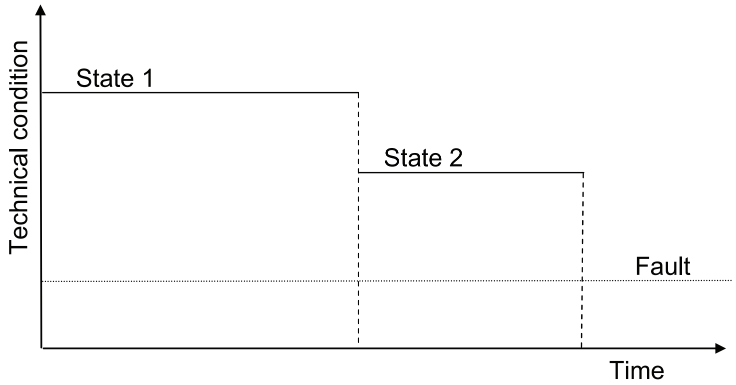

Figure 20 Two-state life curve model – based on Paper IV (Nordgård et al., 2010b).

The life curve represents the time before failure occurs, starting from an *As-good-as-new* condition, via *Degraded* to *Fault*. Estimates for mean sojourn time and 10th percentiles for the failure mode *Slow operation of switch* are presented in Table 9.

Table 9 Mean sojourn times and 10th percentiles in the condition states – from Paper IV (Nordgård et al., 2010b).

Failure mode	State 1 – As-good-as-new		State 2 – Degraded	
	Mean value	10^{th} percentile	Mean value	10^{th} percentile
Operating mechanism causing slow operation of the switch	6 years	2 years	6 years	2 years

Based on these values, using the methodology described in Paper IV (Nordgård et al., 2010b), time varying failure probabilities were computed for the failure mode. For the purpose of this case, the hazard rate, *z(t)*, was chosen to be the most suitable model input parameter. The hazard rate gives an estimate for the number of occurrences in year *t* given that no incidents have happened before that time. This is a suitable measure when using the model to say something about maintenance intervals. The hazard rate, *z(t)*, is illustrated in Figure 21.

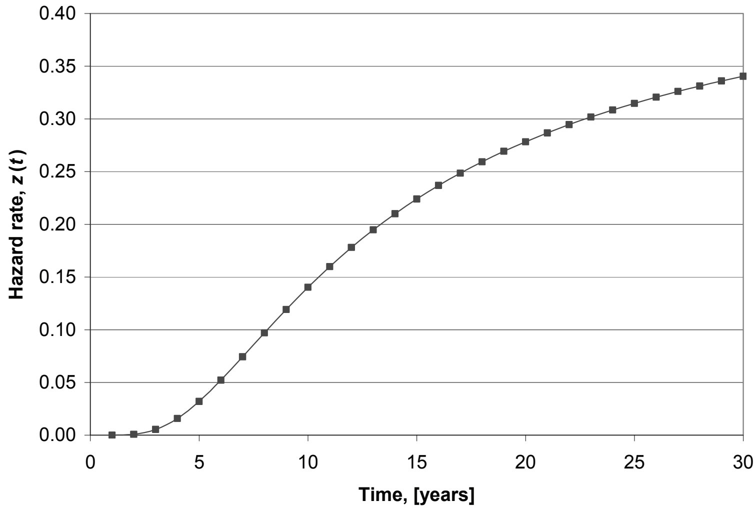

Figure 21 Hazard rate z(t) for the failure mode "Slow operation of switch" – from Paper IV (Nordgård et al., 2010b).

The hazard rate shown in Figure 21 was used as an input to the fault tree and event tree analysis. The event tree used in Paper IV is shown in Figure 22. The details concerning the event tree parameters are described in the paper.

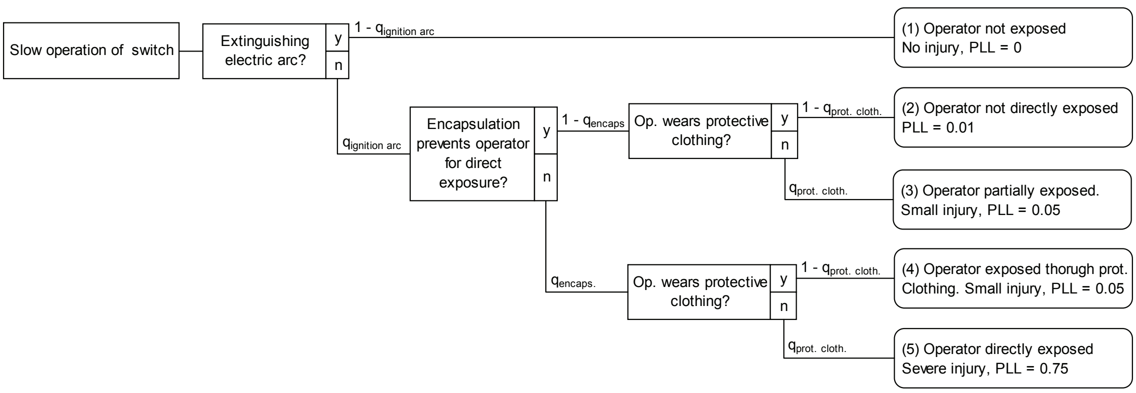

Figure 22 Event tree modelling following the event "Slow operation of switch" – from Paper IV (Nordgård et al., 2010b).

The bow-tie model was analysed for three different types of encapsulations;

- Fully encapsulated switchgear, where the switch disconnector is placed in cubicle covered by steel plates with pressure release in safe directions.
- Semi-encapsulated switchgear, where the switch disconnector is placed behind steel plated cubicle fronts, but the top and bottom of the cubicle is open.
- Wire fence switchgear cubicles, where there are only wire fences between the operator and the switchgear.

The results from the calculation, the safety risk measure, *E(PLL(t)),* are shown in Figure 23.

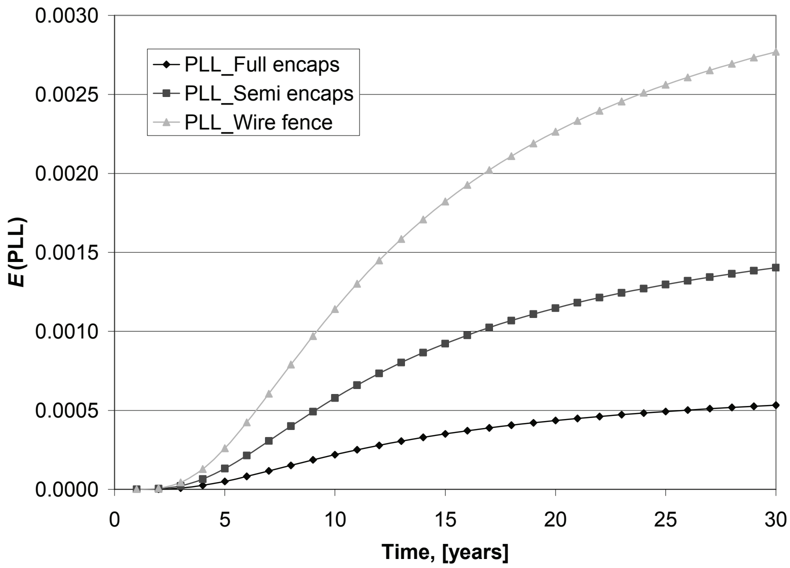

Figure 23 E(PLL) as function of time for three different types of encapsulation – from Paper IV (Nordgård et al., 2010b).

The results show that the wire fence encapsulation results in approximately a five-fold higher safety risk compared to the fully encapsulated switchgear.

Also here it is relevant to ask: What is acceptable risk in this case? Previous practice in electricity distribution companies indicates that 4-5 years (and also more) have been used as a maintenance interval for wire fence encapsulated switch disconnectors.

If 5 years is chosen (*time = 5* in Figure 10), this results in an implicitly given acceptance level of (at least) *E(PLL)* = 0.0003. Transferred to the other types of switch encapsulations, this gives a maintenance interval of approx 7 years for semi-encapsulated and 11-12 years for fully encapsulated switch disconnectors.

5.4.3 Summary of results

The following results summarise the work related to this sub-objective:

- When analysing intangible risks, it is necessary to use expert judgment to estimate model parameters.
- Paper IV (Nordgård et al., 2010b) shows that life curve models are a feasible way of providing input to a QRA model, using expert judgment about condition states and sojourn times as input.
- The proposed procedure in Paper IV states a structured way of using life curve models as input to a bow-tie model, resulting in a time-varying risk estimate that for example can provide a basis for comparing alternatives.

5.5 FRAMEWORK FOR RISK-INFORMED DECISION MAKING IN DISTRIBUTION SYSTEM ASSET MANAGEMENT

This part of the work was undertaken with the aim to use results from some of the other sub-objectives to formulate a framework describing how QRA can be used for decision support in electricity distribution companies. This framework is presented in Paper VI (Nordgård, 2009b), and illustrated in Figure 24.

Compared to the general frameworks for risk assessment (which is one of the parts of risk management described in section 4.2), the proposed framework highlights the use of QRA to analyse selected risk problems.

In Paper VI (Nordgård, 2009b) it is also emphasised that throughout the process it is important to keep in mind the aspect of risk communication to relevant stakeholders.

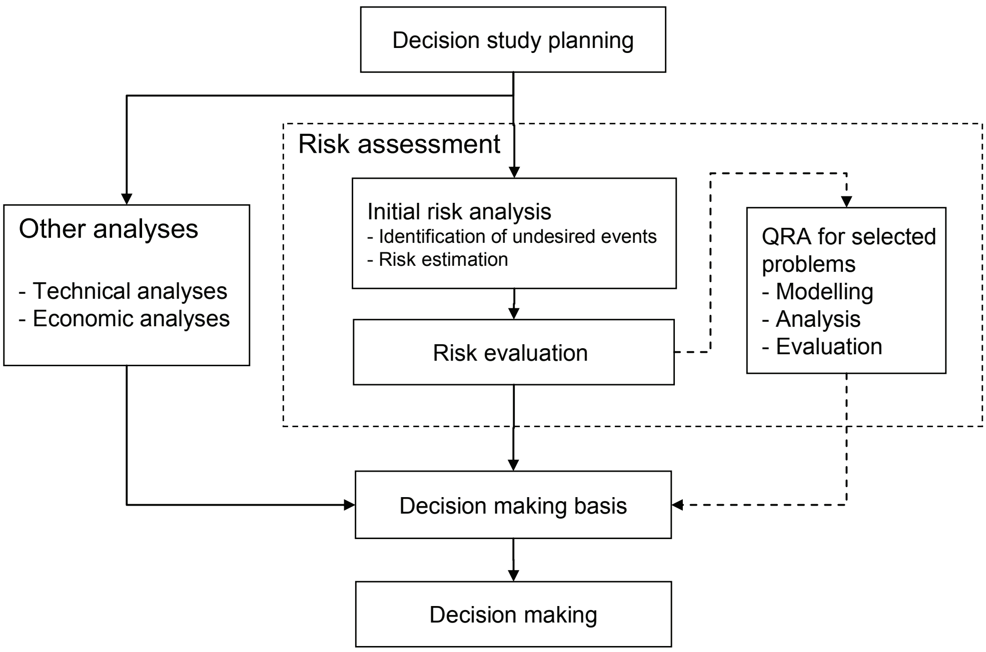

Figure 24 Proposed framework for risk-informed decision support in electricity distribution system asset management – from Paper VI (Nordgård, 2009b).

The different parts of the proposed framework are described in detail in Paper VI (Nordgård, 2009b), but two important aspect, *Initial risk analysis* and *QRA for selected problems* are highlighted in the following.

5.5.1 Initial risk analysis

Risk analysis deals with finding answers to Kaplan's triplet of questions, as listed in section 4.1, through identifying undesired events and estimating the probabilities and consequences of these events.

In the initial risk analysis, it is proposed to use simplified risk analysis methods in combination with risk matrices. This is done to gain an overview of the risks with minimum use of resources, see e.g. (Nordgård and Samdal, 2010).

Identification of undesired events

The aim of this part of the framework is to identify relevant sources of risk and to pinpoint undesired events that might origin from these sources. Input to this can be:

- Expert knowledge,
- Results from inspections,
- Data from databases,
- Results from previous analyses.

Experience shows that only limited information can be found in statistical databases related to the analysis of intangible risks (due to the fact that the information simply does not exist), and previous analyses are also few in numbers. Expert judgment and results from inspections will hence often be the best available sources for identifying undesired events.

Risk estimation and mapping

The risk estimation includes assessing probability and consequence estimates for the undesired events (ISO/IEC, 2002). To map the risk results, risk matrices should be used for each of the consequence categories that are relevant for the decision. Typical examples of such consequence categories can be economic impact, safety, environmental impact and reputational impact, see e.g. (Nordgård et al., 2005, Nordgård and Samdal, 2010)

Potential sources of data for such estimates will be the same as for the sources to identify the undesired events, and expert judgment will also be of great importance in this context. Probability and consequence estimates can be in qualitative or semi-quantitative forms, e.g. "*High*", "*Medium*", "*Low*" or "*1 – 10 occurrences per year*". An example of risk mapping from Paper VI (Nordgård, 2009b) is shown in Table 10.

Table 10 Plotting of 6 undesired events in a risk matrix – from Paper VI (Nordgård, 2009b).

	C_1	C_2	C_3	C_4	C_5
P_5					
P_4					
P_3					
P_2		1(rep.)	1(env.)		
P_1		2(ec./rep.) 5(ec./rep.)	3(rep.) 6(rep.) 4(ec.)	3(saf.) 6(saf.)	

Abbreviations: ec. = Economy, saf.= Safety, env. = Environment, rep. = Reputation.

The probability and consequence scales are denoted with the following qualitative terms (based on (Nordgård et al., 2007b)):

P_5 – Highly Probable	C_5 – Catastrophic
P_4 – Very Probable	C_4 – Serious
P_3 – Probable	C_3 – Medium
P_2 – Less probable	C_2 – Small
P_1 – Improbable	C_1 – Negligible

Risk evaluation

The initial risk mapping will in many cases provide sufficient information concerning the risk picture, and there will be no need for more detailed analyses. The risk evaluation may however reveal risks that may call for a more in-depth investigation, by using QRA methods. Candidates for more thorough QRA modelling can be:

- Critical undesired events,
- Undesired events with potentially large consequences,
- Undesired events where the uncertainty in the initial estimate is high,
- Evaluation of alternative solutions for risks considered unacceptable.

The motivation for performing a QRA is to provide better understanding of the problem and a better basis for making decisions.

5.5.2 QRA for selected problems

The process of using QRA includes (Paper VI (Nordgård, 2009b)):

- Describing the system – including relevant barriers, maintenance actions, etc.
- Establishing models representing causal relations.
- Estimating model parameters.
- Calculating and presenting results.
- Having dialogue and discussions with relevant stakeholders regarding model assumptions, numerical inputs and results.

The results from QRA can provide valuable input to and structuring of the decision problem, as illustrated in section 5.3.

The framework proposed in Figure 24 also emphasises that risk analyses are not the sole input to decision making. Other technical analyses, such as load flow analyses, reliability analyses (which are another type of risk analysis that are outside the scope of this thesis) and various economic analyses will also be important input to the basis for decision making.

5.5.3 Summary of results

The following results summarise the work related to this sub-objective:

- ➢ A framework for risk-informed decision making is described in Paper VI (Nordgård, 2009b). The framework proposes the use of simplified risk analysis methods for initial risk assessment, and QRA methods to perform more in-depth studies of selected problems.
- ➢ QRA methods will be more laborious to perform compared to simplified risk analyses. QRA should therefore be limited to a selected number of problems.
- ➢ The results from the risk analyses will – together with results from also other types of analyses – contribute to a more solid basis for making decisions.

5.6 TESTING AND VERIFICATION THROUGH CASES

The last sub-objective stated for the work was to test and exemplify the methods and approaches through their application in distribution system asset management cases. Table 11 summarises the cases that were used in this thesis.

Table 11 Cases presented in this thesis.

	Method(s)	Case description
Paper I	Bayesian networks	Analysis of safety risk and maintenance options for 12 kV MV switch disconnectors
Paper II	Bow-tie model	Analysis of working routines for decommissioning of LV overhead lines
Paper III	Bow-tie model Reliability importance indicators Sensitivity analysis Monte Carlo simulation	Analysis of potential oil spill from MV/LV transformers, and the impact of uncertainty in input parameters
Paper IV	Bow-tie model Life curve model	Use of expert judgment and life curves as inputs for the analysis of safety risk and maintenance intervals for MV switch disconnectors
Paper VI	Simplified risk analysis Bow-tie model	Risk analysis of MV/LV distribution transformers, including detailed analysis of potential oil spill

Paper V and Paper VII do not contain cases where risk analysis methods have been used.

The cases were chosen based on input from Norwegian electricity distribution companies as examples of risk related problems, and risk analysis was applied to see if the methods can provide useful inputs to such decision making problems.

The cases reflect a range of applications, from making maintenance strategies with respect to safety, to analysis of environmental impacts from potential oil emissions from transformers, and analysis of working procedures for decommissioning of LV overhead lines.

The following results summarise the work related to the last sub-objective:

- The cases have exemplified and illustrated the feasibility of using QRA methods to provide input to distribution system asset management decision making. Feedback from distribution company practitioners indicate that the methods can provide valuable decision support in this context.
- Compared to performing simplified risk analyses only, QRA will give the decision maker(s) a better basis for comparing results for different alternatives.
- The choices of modelling and input data used in the cases, can obviously be debated. In practical use this will be one of the advantages of using QRA, in that it facilitates constructive discussions concerning important risk influencing factors, and how they should be included in the analysis.

6 DISCUSSION

"Looking through a glass onion"[22]

This chapter presents a discussion of the results from the work and an evaluation of the applicability of the results for electricity distribution companies.

6.1 DISCUSSION OF THE RESULTS

The concepts of risk
There are a number of definitions of risk available, as described in sections 4.1 and 5.1, and there is an ongoing debate concerning their appropriateness.

For practical applications in electricity distribution system asset management, the definitions stated in (Kaplan, 1997) and (ISO/IEC, 2002), presented in section 4.1, have shown to be well-suited to the purpose of providing a framework for structured analyses and discussions concerning risk. This is illustrated through the cases included in this thesis.

As of today, the results from the ongoing debate about definitions will not pose a significant change in how to think about risk, at least not for the purpose of the work presented in this thesis. But it is important to be aware of the discussion, and to see if future developments in the conceptual frameworks can contribute to improve risk-informed decision making also in electricity distribution system asset management.

Risk perception and communication
There are many aspects that influence how stakeholders perceive risk, and hence how they judge the acceptability of a risk. It is important to acknowledge these social and psychological aspects of risk management, especially in decision situations where more than one stakeholder is involved. For electricity distribution companies, this can typically involve (members of) the general public or governmental bodies.

Even though there are discrepancies concerning how stakeholders perceive risk, one should not draw the conclusion that risk analysis is of little value as input to decision

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[22] Text line from the song *Glass Onion*, by John Lennon and Paul McCartney, issued on the *White Album*, 1968. *Glass onion* is slang for *monocle*.

making. A structured and transparent risk analysis will document what has been considered when addressing the risk problem, and help to identify the source of potential disagreements and where to look for solutions.

Risk analyses can therefore contribute to align perceptions of risk and provide an arena for communication and problem solving.

Quantitative risk analysis methods used for decision support

The results presented in several of the papers included in this thesis show that QRA methods can structure and analyse problems addressing intangible risks in distribution system asset management. Bayesian networks and bow-tie models have been used for the purpose, and both methods provide results which can give useful input when evaluating risk problems.

To compare the two methods, a qualitative evaluation has been performed taking into account the aspects of:

- Transparency of the methods,
- Computational complexity of the methods,
- Need for data to support the analysis,
- Ability to represent complex relations, and
- Competence required to model risk problems.

These aspects are discussed in the following.

With regards to *transparency*, the bow-tie modelling is considered better, compared to Bayesian networks. In a bow-tie model it is apparent by visual inspection what is included in the model or not. In a Bayesian network more of the cause / effect relations are modelled in conditional probability tables, and hence it may require more investigation to understand the modelling.

The *computational complexity* is further considered somewhat higher for Bayesian networks compared to that of bow-tie models. By this it is meant the possibility for an analyst to understand the results from the model; for example it is considered significantly easier to check a bow-tie model “by hand” (especially the event tree analysis) than to do the same with the results of a Bayesian network.

The *need for data* is also considered to be higher with regards to constructing conditional probability tables in a Bayesian network, compared to the probability estimates used in bow-tie models. Even though the origin of the data will be the same, and stem from the same expert judgment, one will often have to make more assumptions in order to establish data for a Bayesian network.

Concerning the methods' *ability to represent complex relations*, Bayesian networks are considered to be more flexible and better suited than bow-tie models. Complex relations will result in complex fault and event trees, which can be demanding to understand. In a Bayesian network, complex relations can be included in the condition probability functions for the nodes, still leaving a relatively simple overview in the model graph. This aspect will be in somewhat opposition to the aspect of transparency, reflecting that when problems get more complex, the advantage that bow-tie models have concerning transparency, may diminish in the potential confusion of complexity.

Finally; the *competence required* to model risk problems is regarded to be higher when using Bayesian networks compared to that of bow-tie models – due to a more complex computational framework and more specialised methods.

The evaluation can be summarised as shown in Table 12.

Table 12 Qualitative comparison of Bow-tie models and Bayesian networks applied to the types of problems presented in this thesis.

Evaluation aspects	Bow-tie models	Bayesian network
Transparency	High*	Medium – Low
Computational complexity	Medium*	Medium – High
Need for data	Low – Medium*	Medium – High
Ability to represent complex relations	Low – Medium	High*
Competence requirements	Medium*	Medium – High

*The most favourable outcome for each of the evaluation aspects is indicated by *.*

Based on this evaluation, bow-tie models have been regarded as the most applicable method for the type of problems treated in this thesis. The main disadvantages regarding Bayesian networks are considered to be more extensive need for data to construct conditional probability tables and less transparency of the model itself.

One possible approach to combine the strengths of both methods is to use the high-level graphs of Bayesian networks as an aid in the process of capturing the essence of the risk problem, and further to adapt this graph into a more simplified bow-tie model. This was done in (Nordgård, 2008a), but has not been further elaborated further in the PhD work.

Generally, Bayesian networks can be considered to be a more advanced risk analysis approach, which have its main advantages when exploring more composite risk problems, requiring higher expertise and more specialised computational tools. For distribution system asset management, Bayesian networks can be the preferable method when more experience using QRA is gained and better data are available. But for the time being, and for the type of problems analysed in this thesis, this is not the case.

Even though QRA methods result in numerical risk estimates, this will not necessarily make it easier to state whether a risk is acceptable or not, since the question of acceptability is also influenced by the stakeholders' risk perceptions and the values and beliefs of the decision maker(s.) To use risk analysis results to judge the acceptability of risk will require a thorough calibration of risk analysis models and clearly stated risk acceptance levels. For the application within electricity distribution system asset management there is still some way to go before this can be achieved.

Exploring uncertainty in input data in QRA

There will always be uncertainty related to risk analysis modelling and input parameters. Exploring the effects of uncertainty should therefore be an important part of any risk analysis.

For the QRA models explored in this thesis, sensitivity analysis is considered to be the most suitable way to explore uncertainty – giving acceptable results with relatively low computational effort. Reliability importance measures can be used to give direction of where to look for risk reducing measures, but it should be accompanied with sensitivity analysis to illustrate the effect of the changed parameters. Monte Carlo simulation will give a broader risk picture, but it will demand more sophisticated modelling, and the results provided will not give significantly more information compared to what can be provided by sensitivity analyses.

One important aspect that should be highlighted from the exploration of uncertainty, is the fact that risk analyses will provide figures that are subject to some level of uncertainty and that are more or less sensitive to changes in model input parameters. It is hence unrealistic to believe that risk analyses will converge towards a "true value" if only "we get the numbers right".

One should acknowledge that uncertainty is an inherent property of risk, and that it should be explored, rather than attempted to eliminate. This is important to recognise for the risk analyst(s), but also for the decision maker(s) using risk analysis results as input.

Numerical input data for QRA

QRA require numerical inputs for various model parameters, and experience shows that it is hard to find statistical data that can support the choice of parameters when analysing intangible risks. The major data source will therefore (at least in a short-to-medium time perspective) be expert judgment.

To obtain parameter estimates, both direct estimates and results from life curve models have been used in this thesis. Which approach to use depends on the purpose of the study, and what input data that are available. For most of the cases illustrated in this thesis, direct estimates were used, providing reasonable results. But as life curve modelling are getting more developed, being advocated by ongoing research projects, this kind of input data can be used to improve and also calibrate quantitative risk analyses; for example by using input data that are consistent with condition monitoring observations.

The validity of the experts' judgment (concerning both direct estimates and life curve inputs), can obviously be questioned, and such judgments should be used with caution. But it is also very relevant to ask, what is the alternative to the use of expert judgment? Both the options of giving up risk analyses due to lack of data, or taking decisions without any attempt to structure and analyse the risk, seem worse than using a risk analysis approach with explicitly stated expert-based assumptions.

Even though it has been shown that expert judgment can provide valuable inputs to QRA, it is also important to improve the foundation for estimating risk analysis parameters by gathering data from condition monitoring activities and historical performance. Such data can facilitate the use of also statistical approaches to estimate model parameters, as supplement to expert judgment.

Framework for risk-informed decision making in distribution system asset management

The framework presented in Paper VI (Nordgård, 2009b) puts the QRA methods into a broader decision making context.

The framework underscores the need for combining simplified risk analysis and QRA depending on the problem at hand. Compared to simplified risk analyses, QRA methods will provide a better basis for comparing alternatives, although it will require more work to obtain these results.

In many cases it will be sufficient to perform a simplified risk analysis only, since this can provide a risk picture that is considered informative enough for decision making. But in some situations, a more in-depth study should be performed, using QRA to illuminate the problem further and provide a better basis for comparison of alternatives.

It will be difficult to formulate a general rule for when to apply QRA. This will be a "decision within the decision", based on an evaluation of the criticality of identified undesired events.

Testing and verification through cases

Throughout the work, the testing of methods and approaches on realistic cases, has been emphasised. The cases reported in the papers illustrate the feasibility of using quantitative risk analysis for decision support in distribution system asset management.

Some of the cases have been used in several of the papers. For example, the case related to the analysis of potential oil spills from transformers was first used in (Nordgård and Solum, 2009), then updated and expanded to include methods to explore uncertainty in QRA in Paper III (Nordgård, 2010), and also combined with a simplified risk analysis in Paper VI (Nordgård, 2009b).

The same risk problem was also used as basis for the cases in Paper I (Nordgård and Sand, 2009), described in section 5.3.1, and Paper IV (Nordgård et al., 2010b), described in section 5.4.2. Even though the cases were not designed for it, it is unavoidable that some comparison is made. What can be seen is that the general trend in the results is the same, even though the numerical values differ. The reasons for the differences can be explained by the fact that different aspects were included in the models and different input data were used. For example; in the case in Paper I, a stepwise constant failure rate was used, while in Paper IV, time varying failure rates from life curves was used. The numerical values used for the barriers were also different.

The somewhat diverging numerical results emphasise that one should be careful in comparing risk analysis results that originate from different models, without first performing a thorough calibration.

Finally, it can also be questioned if it is necessary to use QRA methods to analyse risk problems as exemplified in this thesis. It is the author's opinion that such analyses can contribute to better understanding of risk problems, and that they hence (in some cases) should be performed. But the cases also show that even simple problems will require quite complex models, and there is a potential danger that the analyses will go into devastating detail. Therefore one will always face the challenge of deciding when to stop and what simplifications to accept in the analyses.

6.2 APPLICABILITY IN ELECTRICITY DISTRIBUTION COMPANIES

As stated in section 1.3, the PhD work has emphasised on the potential practical application of risk analysis methods in electricity distribution company decision making.

The work performed in this thesis shows the feasibility of using QRA for decision support, but it is still valid to ask if the methods and results are applicable for use in distribution system asset management among Norwegian electricity distribution companies. As of today, there is no – or at least very limited - use of such quantitative methods to analyse intangible risk.

The process of developing risk-informed decision making can be seen on as consisting of several steps; for example:

- Understanding the fundamental concepts of risk and risk analysis,
- Applying simplified risk analyses in a structured and well-founded manner,
- Using QRA methods to elaborate more thoroughly on selected problems.

Several companies have gained experience on the first two steps of such a process, having built a foundation for their future risk management. The inclusion of QRA in their asset management decision making is therefore within reach, but it will require new ways of thinking and new expertise among company professionals.

To summarise; it can be stated that risk analysis in general, and QRA methods in particular, can contribute to better decision support and documentation of risk assessment in electricity distribution companies. The use of such methods should however follow the principles of continual improvement (as described in section 3.2), starting with basic applications, and sophisticating the approaches as experience and confidence is gained.

In (Apostolakis, 2004), three phases in the application of QRA are outlined, based on the experiences from the nuclear energy sector and space exploration:

- *Phase 1* is characterised by scepticism about the usefulness of such approaches.
- *Phase 2* is when engineers and decision makers get more used to the methods, and start paying attention to the insights provided by QRA. Typically, decision makers focus on the "negative insights", for example through taking into account failure modes which previously have not been identified.
- *Phase 3* is reached when confidence is gained in the methods, which allows also for using the "positive insights", for example through relaxing previously imposed safety requirements because the new insight give reason to prioritise otherwise.

If similar phases are to be observed within electricity distribution, is yet unknown. But since the distribution companies can use the insights of QRA to improve their asset management practices, it can be worth the effort of trying to follow the footprints of nuclear and rocket science.

7 CONCLUSIONS AND FURTHER WORK

"The end"[23]

This chapter presents conclusions from the work, and proposes topics for further research.

7.1 CONCLUSIONS

The work presented in this thesis contributes to the fulfilment of the overall objective, which has been to explore risk analysis methods that can be used to support decision making in electricity distribution system asset management, with an emphasis on the analysis of intangible risks. This has been achieved through the elaboration of sub-objectives that together address the composite overall objective.

The main contributions of this thesis can be summarised as:

- An exploration and testing of quantitative risk analysis (QRA) methods to support decisions concerning intangible risks.
- The development of a procedure for using life curve models to provide input to QRA models.
- The development of a framework for risk-informed decision making where QRA is used to analyse selected problems.

In addition, the thesis contributes to clarify the basic concepts of risk, and describe concepts and challenges related to risk terminology, risk perception and risk communication; recognising that risk analysis and risk management have facets that go beyond the methods for analysis and acquisition of data.

Risk analysis in general, and QRA in particular, can provide a more solid foundation for making decisions, but it should be emphasised that it will not deprive the decision maker neither the privilege nor the responsibility of making the final decision.

[23] Song by John Lennon and Paul McCartney, issued on the *Abbey Road* album, 1969.

7.2 FURTHER WORK

The work presented in this thesis has explored several aspects related to risk analysis that are relevant to distribution system asset management. The work has also revealed issues that still need to be addressed. Some research tasks are proposed in the following:

Perform studies concerning risk perception and communication in electricity distribution companies.
Risk management in electricity distribution companies have so far been concentrated on the technical aspects of risk analysis. As stated in sections 4.2 and 5.2, there are also social and psychological aspects of risk which are highly relevant in decision making contexts. It would be relevant to investigate this further; for example through looking closer into potential differences in perception of risk among various stakeholders.

Test and evaluate the use of formal multi-criteria decision making methods applied to the analysis of multi-dimensional risk problems.
It is evident that decision making in electricity distribution asset management very often will include more than one decision criterion. Multi criteria decision making (MCDM) methods are hence highly relevant candidates to support decision making, as illustrated in e.g. (Nordgård et al., 2003, Catrinu et al., 2007, Catrinu and Nordgård, 2010). It has been beyond the scope of this thesis to go into MCDM theory and methods, but such approaches should be further explored for their usefulness in e.g. aggregating multiple risk analyses results into a common decision framework.

Investigate ways of using expert judgment and also other data sources to provide input to risk analysis.
The cases presented in this thesis show the need to rely on expert judgment when analysing intangible risks in electricity distribution system asset management. Direct estimates and life curves models have been applied in this work, but there are also other methods that can be applicable to provide input data (including both expert judgment and other data sources). It would therefore be useful to investigate further on how to provide data for QRA in this context.

Develop tools for risk analysis in electricity distribution companies.
In order to make risk analyses in general and QRA in particular more available for distribution companies, there is a need to develop tools intended for practical implementation in decision making. This is an area of research that could make risk analysis methods more available and adapted for the specific purpose of risk analysis in electricity distribution companies. This work can also contribute to validate the usefulness of such analysis methods in asset management.

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PART II – PAPERS

Paper I

Paper I. "**Application of Bayesian belief networks in electricity distribution system maintenance management**".

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Application of Bayesian networks for risk assessment in electricity distribution system maintenance management

D. E. Nordgård
Norwegian University of Technology and Science, Trondheim, Norway

K. Sand
SINTEF Energy Research, Trondheim, Norway

ABSTRACT: Electricity distribution companies regard a risk-based approach as a good philosophy to address challenges of asset management, and there is an increasing trend on developing maintenance strategies where different aspects of risks are taken into consideration. This paper illustrates the use of Bayesian networks (BNs) to model safety risk as a part of maintenance decision making. A case study is included illustrating the use of BNs to investigate the risk impact of different maintenance intervals of MV electrical switches. The case study uses input from expert judgment to establish the qualitative relations and quantitative figures in the BN. The paper summarises some challenges and benefits of using BNs as a part of distribution system maintenance management.

1 INTRODUCTION

During the last decade the electricity distribution sector has been ever more focusing on asset management as the guiding principles for their activities - see e.g (Brown & Spare, 2004) and (Kostic, 2003). *Maintenance* is an important part of the asset management scheme, as a means of controlling the companies' risk (BSI, 2004).

There is now an increasing trend among distribution companies on developing maintenance strategies where different aspects of risk are sought included in a holistic way. The different consequence categories of risk relevant for distribution companies include economy, safety, reputation, environmental impact, quality of supply and fulfilling of contractual obligations (Brown & Spare, 2004; Nordgård et al., 2007a; Sand et al., 2007).

The distribution companies regard a risk-based approach as a good philosophy to meet the overall asset management challenge. For some of the risks there are methods and tools already used within the electricity distribution sector – such as economical risk analyses and quality of supply risk analyses (reliability analyses). For others – e.g. safety issues - there is less culture and practice for performing structured analyses to support decisions. In some cases semi-quantitative methods have been applied to analyse and document priorities and decisions regarding maintenance, e.g. using risk matrices (Nordgård et al., 2007b).

Deciding maintenance activities have until now been based largely on existing practice, producers recommendations and to some extent direct regulation from authorities, with little application of formal analyses within the electricity distribution companies to support or reject the existing paradigms.

The electricity distribution companies therefore have potential to improve their analytical approach of maintenance assessment, in order to increase understanding, find solutions and optimise the spending on maintenance activities. This is also supported by an increasing demand from authorities for the companies to perform and document risk assessments.

This paper addresses the challenge of including formal and structured risk assessment in electricity distribution maintenance management, focusing on application in medium voltage (MV) systems. The paper describes the application of Bayesian networks (BNs) for modelling and analysing maintenance strategies and their impact on occupational safety. The application is illustrated by an example analysing MV switches. The paper concludes with some remarks on benefits and challenges which distribution companies are facing when using such methods as a part of their maintenance management.

2 MV ELECTRICITY DISTRIBUTION SYSTEM MAINTENANCE MANAGEMENT

MV electricity distribution systems are the electricity distribution infrastructure on voltage levels from 1 to 35 kV, connecting the transmission and subtransmission grids to the regular customers of the low-voltage (LV) distribution level.

MV distribution systems are characterized by being widely geographically dispersed and having vast numbers of components. Component lifetimes are typically 30 to 60 years, but there are large variations around the average values.

The condition of the distribution system directly affects the quality of supply to end-use customers. Due to its widespread distribution, huge numbers of components and little degree of remote control and automation, this infrastructure is also important with regard to safety aspects of both operators and third parties.

Most of the MV distribution systems have been built during the last 50 years, and the distribution companies are now facing the challenges of ageing and end-of-life issues. Hence, maintenance and reinvestment strategies have a more prominent position than before on the companies agendas. Distribution companies recognise a general need for methods and tools to support maintenance and reinvestment decisions in a structured manner (Sand et al., 2007).

Risk assessment for different consequence categories should play an important role when establishing maintenance strategies. Risk assessment can be performed by various methods – from informal approaches to more structured and analytical ones. One group of methods are *Quantitative risk assessment* (QRA) methods, which are analytical methods used to explicitly model causal relations and achieve quantitative measures of risk (Apostolakis, 2004).

The application of QRA methods can be advantageous for different tasks of maintenance management. One example of the usefulness of QRA is the ability to structure input data (expert knowledge and/or statistical data) into an analytical framework for analysis of specific problems of concern, e.g. safety related issues.

QRA results should never be the sole basis for decision making, but rather be a part of the decision basis, contributing to better decisions than would be the case without risk assessment inputs (Apostolakis, 2004). One should therefore not forget that the purpose of any risk assessment should not be to prescribe the "correct" solution, but rather to provide insight and understanding – and thus contribute to a risk informed decision basis.

Bayesian networks (BNs) is one of the promising QRA methods which is applicable for assessment of quantitative measures of risk. The general modelling capabilities of the method can applied to a variety of risk related challenges (Langseth, 2007).

The following section gives a brief description of the principles of BNs.

3 BAYESIAN NETWORKS SUPPORTING RISK ASSESSMENT

Bayesian Networks is a modelling framework which has been used in many domains of application, e.g. diagnostic systems and general reliability modelling.

BNs generally offer a compact presentation of the interactions in a stochastic system by visualizing system state variables and their dependencies. Due to their versatility, it is of interest to test the usefulness of BNs in electricity distribution system risk management.

BNs have shown to be a robust and efficient framework for dealing with uncertain knowledge. They represent a modelling framework which is easy to use in interaction with domain experts.

A BN consists of two main parts: a qualitative part; and a quantitative part. The qualitative part is a directed acyclic graph where the nodes mirror the random variables, and the edges of the graph represent the conditional dependence between variables. The quantitative part is a set of conditional probability functions.

3.1 *Simple illustration*

Figure 1 shows a simple example of a Bayesian network established to model how vegetation growth and adverse weather may influence the occurrence of overhead line interruptions in electricity networks.

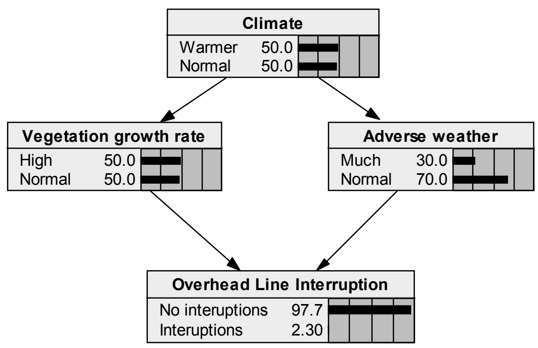

Figure 1 Simple example of Bayesian network

The network consists of four two-state random variables given by the nodes in the graph:

- *{Climate}*
- *{Vegetation growth rate}*
- *{Adverse weather}*
- *{Overhead line interruption}*

The arrows in the diagram represent dependencies between nodes and can be interpreted as causal relationships. Hence, the probability of overhead line interruptions is dependent on the two parent nodes: *{Vegetation growth rate}* and *{Adverse weather}*.

The example also indicates a causal relationship between the overall node *{Climate}* and both *{Adverse weather}* and *{Vegetation growth rate}*.

The arrows in the graph represent the assumption that a variable is conditionally independent of its non-descendants given its parents in the graph. Hence, *{Overhead line interruption}* is conditionally independent of *{Climate}* given the parent nodes *{Vegetation growth rate}* and *{Adverse weather}*.

The underlying assumptions of conditional independence encoded in the graph allow calculating the joint probability function as:

$$f(x_1 \ldots x_n) = \prod_{i=1}^{n} f(x_i | pa(x_i)) \quad (1)$$

Hence, the conditional probability can be calculated, e.g. the probability of overhead line interruption given the parents:

f(Overhead line int.|Adv. weather, Veg. gr. rate) (2)

One of the interesting properties of BNs is that they can be extended to represent decisions using so-called influence diagrams (Langseth, 2007). The basis for the representation is utilities, which are quantified measures for preference. Exploiting the probability updating of the BN framework, it is easy to calculate the expected utility for each decision option for a modelled case.

4 EXAMPLE OF APPLICATION – RISK MODELLING OF MV AIR INSULATED SWITCHES

To illustrate the potential application of BNs in maintenance management, an example is provided where a BN is used for safety risk assessment.

4.1 *Description of the system*

The modelling of air insulated switches is based on work done in cooperation with Norwegian distribution companies. A semi-quantitative risk assessment was performed where relevant risk influencing factors were identified and discussed based on the knowledge of company experts (Nordgård et al., 2005). The risk analysis is now taken further using a Bayesian network.

The analysis is focused on safety aspects regarding 12 kV air insulated switches in indoor MV/LV substations. The switches in question are not regarded as particularly unsafe, but since there are quite a large number of them in service, they have been chosen for closer analysis.

The switches are used to break load current when sectioning the MV distribution network. In the transient period after the opening of the switch – when there is no longer physical contact between the switches' poles – the current will continue to flow through an electric arc until the natural zero-crossing of the alternating current.

Normally the electric arc will then extinguish in a controlled manner, and the breaking of the current is successful. However, in some cases the arc will reignite and current will continue to flow through the electric arc, generating energy dispersion through heat (with accompanying pressure rise).

The main reason for electric arcs not to extinguish is, in our case, assumed to be slow movement of the switch during operation. When the switch operates slowly, there will be less cooling of the arc, and the arc has time to establish stable burning conditions. (It should be noted that the electric arc usually will be detected by upstream protection devices de-energizing the system and will not burn for a long period of time. But since the energy dispersion is high, even short duration electric arcs will involve hazards.)

The failure mode of slow operation of the switch is the initiating event in the risk scenario presented in this example. When slow operation of the switch occurs, there are still barriers which can prevent the situation from becoming a threat to safety:

- The electric arc might still extinguish (for example due to too small load current to obtain viable arcing conditions).
- The cubicle encapsulating the switch can protect the operator from the electric arc.
- The operator can wear protective clothing – that prevents physical injury in case of exposure to an electric arc.

Three encapsulations are considered in this example:

- full encapsulated switch (*steel plate covered cubicles, with pressure relieving outlets in safe directions*)
- semi encapsulated switch (*steel plated cubicle fronts, but the top and bottom of the cubicle is open*)
- wire fence switch cubicles (*only wire fences - supplies little protection from electric arcs coming from the switchgear*)

The reason for the differences in encapsulation is that the substations have been built over quite a long period of time, during which the technical solutions have improved from the wire fence solution to the full encapsulated switches.

Figure 2 shows a sketch of the operating situation, where the operator stands in front of the cubicle while operating the switch by pulling an inserted handle.

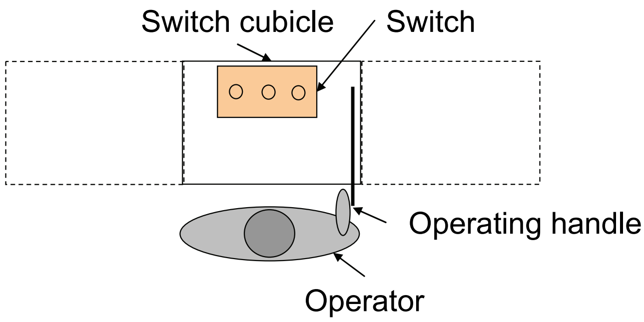

Figure 2 Top view sketch of the situation when operator handles the switch

4.2 *Risk influencing factors*

The following factors have been identified by company experts as relevant for differentiating the population of switches with regard to risk:

- switch age
- operating environment
- maintenance interval
- encapsulation of the switch.

The use of protective clothing will also influence the safety risk.

4.3 *Bayesian network modelling*

A Bayesian network – shown Figure 3 - is constructed to perform a structured and quantitative modelling of this safety related problem.

The network contains altogether 11 different nodes, of which 6 nodes have conditional probability tables that are functions of their parent nodes.

The documentation for all of the conditional probability tables are not included in this paper, due to limited space, but the most important features are explained in the following.

4.4 *Slow switch operation*

Two states are identified as being critical with regards to the correct operation of the switch: *Switch poles stuck* and *Slow operating mechanism*. Both states affect the probability of slow operation of the switch, which is regarded as critical with respect to safety due to the possible exposure of the switch operator to a burning electric arc.

The same maintenance action – functional control – will affect both of the critical states. The choice of maintenance interval, τ_m, is modelled as a decision node in the network.

4.4.1 *Switch poles stuck*

The node *Switch poles stuck* is modelled as dependent on the age of the switch, its operating environment and the maintenance intervals used. The node is represented by two states only:

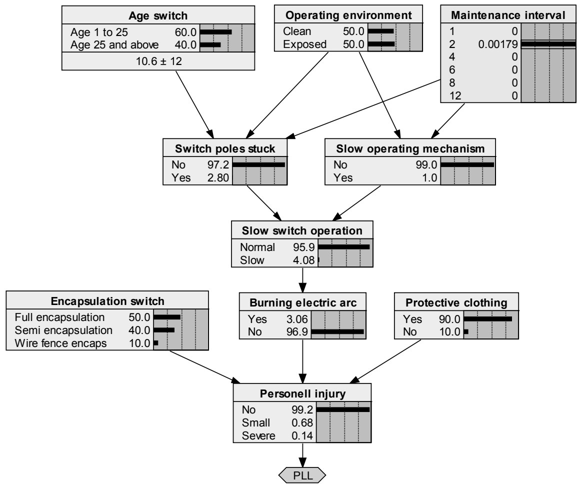

Figure 3 Bayesian network for safety model for air-insulated switches

No (meaning that the switch poles are OK) and *Yes* (meaning that the poles are more or less stuck which gives possible slow operation of the switch).

The base value for the failure rate for this failure mode is chosen to be λ_{pole} = 0.01, based on expert judgements.

4.4.1.1 Age of the switch

The failure rate is modelled as being constant within given time frames. Based on discussions with experienced company experts, 25 years is chosen as threshold value in the failure rate modelling. It is assumed that switches aged 25 years or older have a failure rate which is twice the failure rate of newer switches. This is illustrated in Figure 4. It is of course an approximation, but regarded to be the best available estimate.

4.4.1.2 Operating environment

The operating environment is regarded as a factor that influences the probability of failure of the switches. For the purpose of categorisation, a two-level qualitative scale has been used: *Clean* and *Exposed* operating environment. A switch operating in a clean environment is assumed to have a failure rate 1/3 the failure rate of a switch in an exposed environment.

The categorisation is also a rough approximation, but it is used by distribution companies in their semi-quantitative approach (Nordgård et al., 2005). It is therefore also used for risk differentiation in this model. The modelling is illustrated in Figure 4.

4.4.1.3 Unavailability modelling

Using the approximation of a constant failure rate, the unavailability due to the failure mode *switch poles stuck*, q_{pole}, is modelled as

$$q_{pole} = \frac{\lambda_{pole} \cdot \tau_m}{2} \qquad (3)$$

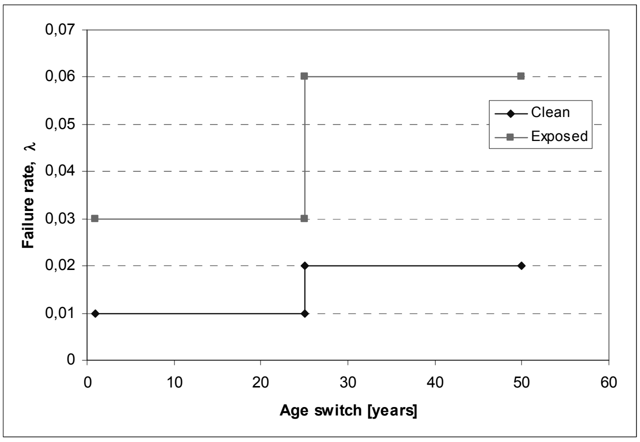

Figure 4 Failure rate modelling for the switch poles, λ_{pole}, in *Clean* and *Exposed* environment as function of age

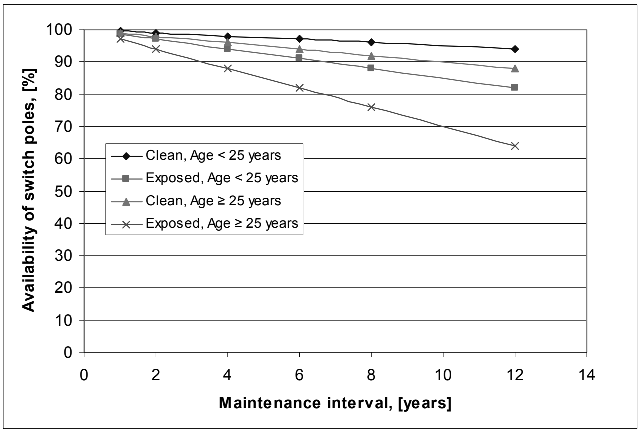

Figure 5 Availability of switch poles as function of maintenance interval for different alternatives

where τ_m is the maintenance interval in years (Vatn, 1997).

The availability of the switch poles for various configurations is illustrated in Figure 5.

In the Bayesian network the data shown in Figure 5 is included in a conditional probability table stating the probability for the switch poles being stuck.

4.4.2 *Slow operating mechanism*

The node *Slow operating mechanism* is modelled as being dependent on the operating environment and the maintenance intervals. The node is represented by two states: *No* (meaning that the operating mechanism is OK) and *Yes* (meaning that the operating mechanism is slow which gives the possible slow operation of the switch).

The base value for the failure rate for this failure mode is chosen to be $\lambda_{op.mech} = 0.005$.

4.4.2.1 Operating environment

A switch operating in a clean environment is assumed to have a failure rate 1/3 of the failure rate of a switch in an exposed environment.

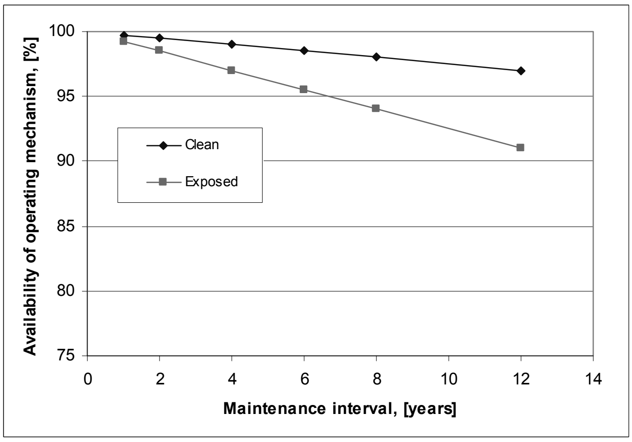

Figure 6 Availability of the operating mechanism as function of maintenance interval

4.4.2.2 Unavailability modelling

The unavailability due to the failure mode *slow operating mechanism*, $q_{op.mech}$, is modelled as:

$$q_{op.mech} = \frac{\lambda_{op.mech} \cdot \tau_m}{2} \qquad (4)$$

where τ_m is the maintenance interval in years. The availability of the operating mechanism in the two different operating environments is shown in Figure 6. The data shown in Figure 6 is represented by a conditional probability table in the BN.

The impact of the two failure modes on the main unwanted event *Slow operation of the switch* is modelled by the conditional probability table shown in Table 1. The modelling reflects that the slow operating mechanism is considered the most serious failure mode.

Table 1 Conditional probability table for slow operation of the switch

Switch poles stuck	Slow operating mechanism	Slow operation of switch Normal [%]	Slow [%]
Yes	No	20	80
Yes	Yes	1	99
No	No	99	1
No	Yes	10	90

4.4.3 *Personnel injury*

It is assumed that 75 % of all cases of slow operation of the switch result in a burning electric arc.

The potential injury to people is dependent on the possible burning electric arc, the encapsulation of the switch and whether the operator is wearing protective clothing or not.

The states of the model are shown in Table 2.

Table 2 Excerpts from conditional probability table – probability of injuries from burning electric arc with different combinations of encapsulation and protective clothing

Burning arc	Encaps-ulation	Protective clothing	Injuries No [%]	Small [%]	Severe [%]
Yes	Full	Yes	90	10	0
Yes	Full	No	75	20	5
Yes	Semi	Yes	75	22.5	2.5
Yes	Semi	No	50	40	10
Yes	Wire	Yes	0	75	25
Yes	Wire	No	0	25	75
No	*All*	*All*	100	0	0

To aggregate the impact of injuries into a single measure, *Potential Loss of Life* (PLL) is used to weigh the severity of the various types of injuries. Table 3 summarises the weights which have been used in the model to aggregate the impact of different injuries into a measure for the aggregated number of fatalities. No injury adds 0 to the total PLL, while a severe injury contributes 0.8 to the total PLL.

Table 3 PLL modeling from the different degrees of injuries

Injuries	PLL
No	0
Small	0.1
Severe	0.8

4.5 *Results from model analyses*

The quantitative safety risk assessment model established in the BN can be used to increase the experts' understanding of the problem and to see how their input to the BN aggregate to results in terms of estimated PLL for the alternative configurations.

It should be emphasised that the absolute value of PLL should be used with caution, but the relative results for the different analysis alternatives give comparable results which can be used to quantify the differences between alternatives.

4.5.1 *Systematic parameter changes*

By systematically changing the parameters in the model, one can obtain results which provide input to the decision basis.

Figure 7 shows that the safety risk related to the switches is estimated to be approximately 20 times higher for the switches in the wire fence encapsulations than for the full encapsulation, and that the doubling of maintenance intervals less than doubles the estimated PLL.

Figure 8 shows that to obtain the same estimated PLL level one can have approximately 3 times longer maintenance intervals in a clean operating environment, than in an exposed operating environment.

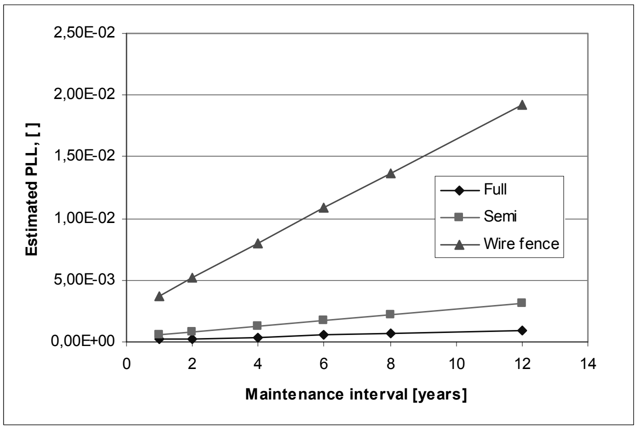

Figure 7 Estimated PLL for three different encapsulations as function of maintenance interval

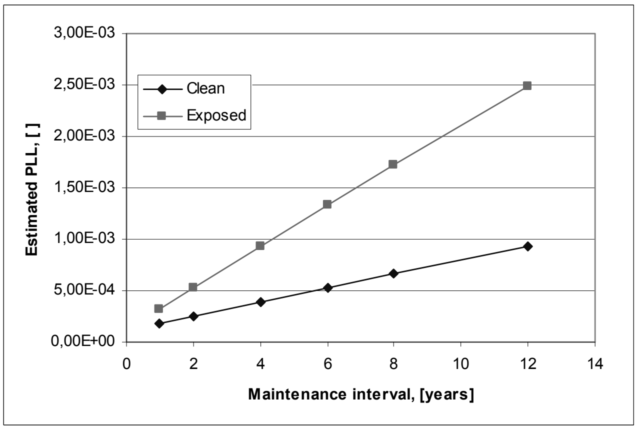

Figure 8 Estimated PLL for Clean and Exposed environment as function of maintenance interval (Full encapsulation only)

Such results may contribute to differentiating the maintenance intervals depending on the risk influencing factors, in order to spend maintenance resources where it is needed the most.

4.5.2 *Updating the model*

The model can also be used to simulate the effect if the state of one or more variables in the model is known. Figure 9 shows the BN updated with the knowledge that the switch poles are in a poor condition, and that the switch cubicle has a wire fence encapsulation. The probability of a severe injury has now increased by more than two orders of magnitude compared to the expected value; this may result in a decision of not to operate such a switch unless de-energized.

5 CONCLUDING REMARKS

Bayesian networks are an appealing method for quantitative risk assessment due to their versatility for different problem situations. This paper illustrates the application of a Bayesian network to model a safety risk maintenance challenge where the

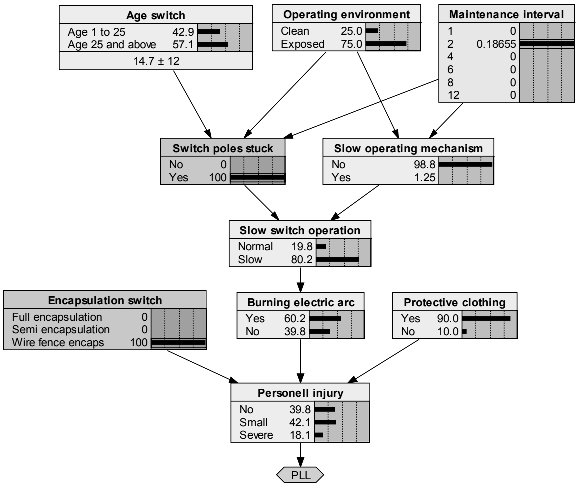

Figure 9 Bayesian network model updated with information about the states of nodes.

results contribute to establishing a risk informed basis for making maintenance decisions.

In the example, a Bayesian network is used to structure and quantify the knowledge and assumptions of the company experts into an analytical model. The explicit modelling may also help to identify whether vital input is missing, and thus identify topics for closer investigation.

The purpose of the modelling has not been to create an "objective and true" model of the problem at hand, but rather to encourage and increase learning and understanding, and to provide a structured framework for risk communication and discussions.

The qualitative and quantitative input to the example was provided by judgements of experts and the analysts, because no relevant statistics were available. Generally, to provide input data for the representation of conditional probabilities in the network, one should look into what sources are available – both from statistical analyses and from expert judgements or, preferably, the combination of both. This is one aspect which obviously should be further emphasised when working with establishing such quantitative models.

The example illustrates that even a relatively simple example requires quite a comprehensive modelling of conditional probabilities. Hence the application of BNs for QRA should be used with some caution.

The electricity distribution companies today are motivated by the customers and the regulators to cut costs so that tariffs could be lowered. Reducing maintenance and reinvestments are cost-cutting options that have to be weighed against increased risk that cost reductions might impose on safety, quality of supply etc. Distribution companies might do well to incorporate analytical approaches to prescribe maintenance strategies, e.g. through using quantitative risk assessment methods to have better risk control, to optimize the spending of maintenance resources, and to increase the understanding of where to focus the companies' attention and efforts.

ACKNOWLEDGEMENTS

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Paper II

Paper II. "**Quantitative Risk Assessment for decision support in electricity distribution asset management**".

Dag Eirik Nordgård.

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Paper III. “**Exploring uncertainty in quantitative risk assessment used for decision support in electricity distribution system asset management**”.

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CRC, Leiden 2010.

Paper III

Exploring uncertainty in quantitative risk assessment used for decision support in electricity distribution system asset management

D.E. Nordgård
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: There is a trend among electricity distribution companies towards using risk assessment for asset management decision support. This paper highlights some aspects of exploring uncertainty in risk analyses, through using reliability importance measures, sensitivity analyses and Monte Carlo simulations. The approaches are exemplified in a case analyzing potential oil spill from distribution transformers. The case illustrates that risk analysis results are not objective, crisp values – but uncertain figures which are more or less sensitive to changes in risk model input parameters. This is an important aspect to acknowledge when utilising risk analysis results in decision support.

1 INTRODUCTION

In Norway, there is a trend among electricity distribution companies towards using risk assessment for decision support in their asset management – see e.g. (Nordgård et al. 2005; Istad et al. 2008). The distribution company risks cover many consequence categories, incorporating tangible as well as intangible risks, e.g. safety, quality of supply (including reliability), environmental impact and economy (Sand et al. 2007).

Historically, risk assessment methods concerning reliability analyses in power systems have been given much attention, with numerous methods available and still being developed – see e.g. (Billinton et al. 2001; Xie & Billinton 2009).

However, for the other risk consequence categoriesthere has been a lack of structured analyses available. The electricity distribution companies therefore see the need to develop methods and tools to support decisions also within these areas. Risk analyses (for other purposes than reliability analyses) are hence being developed, tried and evaluated – see e.g (Hamoud et al. 2007; Nordgård 2008; Nordgård & Sand 2008).

This paper shows how quantitative risk assessment (QRA) can be applied to analyze intangible risks, with special emphasis on approaches for including uncertainty in the analyses. It first gives a brief description of risk and uncertainty in electricity distribution – stating the basis for how we look at uncertainty in this context. It further presents three approaches for exploring uncertainty in QRA. The approaches are exemplified through a case where a bow-tie model is used to analyze environmental risk related to accidental emissions of transformer oil. The paper concludes with some remarks concerning what can be achieved through exploring uncertainty explicitly in risk analyses.

2 RISK-INFORMED DECISION MAKING IN ELECTRICITY DISTRIBUTION

2.1 *Risk decision problems*

Almost every activity will include risk, and even though striving to reduce it, it will be impossible to achieve a complete elimination of risk. Hence we will always face the problem of what is acceptable risk (Fischhoff et al. 1981; Vatn 1998).

In electricity distribution asset management, we want to use risk assessment as a tool to analyze risk, to provide increased understanding of the risk problem and to structure and document the results. The aim is to provide input to the decision making process, where the acceptable risk problem is addressed.

2.2 *Uncertainty*

Uncertainty – the fact that there are things that we do not know – is a prerequisite for risk, and should be kept in mind throughout risk assessment and decision making.

Like 'risk', the term 'uncertainty' is used with different interpretations in the risk analysis society. In some contexts a distinction is made between decision made under uncertainty (meaning decision situations with unknown probability distributions), and decision made under risk (meaning decision situations with known probability distributions).

If we should have used this terminology for decision making concerning intangible risk in electricity distribution systems, we would most probably be talking about 'decisions under uncertainty' – since the knowledge and data available rarely will provide known probability distributions. However, the broadly accepted term for such analyses is *risk analyses*, and hence we shall use this term in this paper.

In other contexts we encounter the distinction between *aleatory* uncertainty (due to the stochastic nature of a process or system) and *epistemic* uncertainty (due to our lack of knowledge) – see e.g. (Stamatelatos et al. 2002). This distinction can be useful to recognize the fact that even with 'perfect' information available, there will still be uncertainty related to our decisions – i.e. that the decision making process will not converge into a deterministic analysis no matter the extent of our knowledge.

For the purpose of this paper we will not elaborate further on distinction between the two conceptual parts of uncertainty, and will address uncertainty in a common term – representing the fact that *we do not know*, focusing on uncertainty in risk analysis input parameters. This use of the term is in line with e.g (Aven 2008).

2.3 *Setting the scene for distribution system asset management*

The decision maker(s) in distribution system asset management will typically be the asset manager(s) in the companies. Decision support is needed to address risk in a structured manner.

One challenge when analyzing intangible risks within electricity distribution is that there is little experience with such analyses, and hence a lack of analyzing competence.

Another challenge is the availability of data to use in the risk analyses. Our experience indicates that relevant historical data are hard to find when addressing intangible risks (Nordgård et al. 2005). Promoting the hunt for data is a task that should also be addressed in the years to come, but we can not sit around waiting for "hard data" to arrive, because decisions still have to be made.

Expert judgment will hence be the input we can rely on, representing the best available knowledge based on system understanding and experience (Apostolakis 2004; Nordgård 2008).

The input from distribution company experts may e.g. be elicited as:

- "My best guess is that there is a 5-10% change for a failure on this component during the next year. But it might as well be twice this number."
- "I think that the introduction of this barrier will almost eliminate the chance of the most severe consequences – let's say a barrier efficiency of 95-100 %."

With this type of statements as basis for estimating numerical input to the risk analyses, there is an apparent need to investigate the "what-if's" - i.e. to perform analyses where the effects of changing input parameters are investigated and evaluated.

Our aim is to make the uncertainty of expert judgment explicitly included in the risk analysis, making the uncertainties a transparent part of the decision making basis.

2.4 *Quantitative risk assessment as input to decision making*

Risk assessment is a central part of the process of providing input for decision making, and this can be performed using different types of methods - from qualitative to quantitative ones.

In this paper we explore quantitative risk assessment using a bow-tie model to analyze intangible risk – combining fault tree analysis and event tree analysis in order to establish the cause/effect relations describing a specific undesired event, see e.g. (Vatn et al. 1996).

A conceptual bow-tie model is shown in Figure 1.

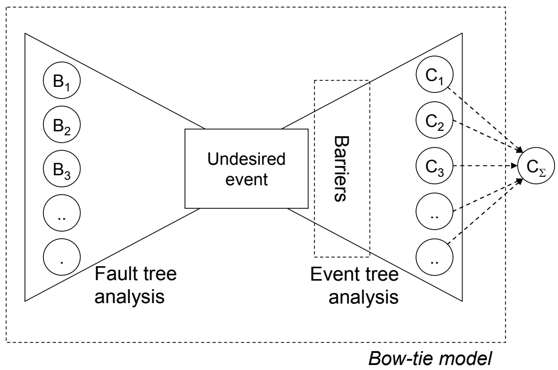

Figure 1 A conceptual bow-tie model.

B_i represents basic initiating events in the fault tree analysis, leading to an undesired event, and C_j represents different possible end events resulting from the event tree analysis. C_Σ are the aggregation of the consequences of all end events into a common risk measure.

2.5 *Methods to explore the effects of uncertainty in risk analyses*

The motivation for exploring the effects of uncertainty in risk analyses, are that we want to see how changes in input parameters will affect the risk analysis results; Will perturbations in input parameters give significant impact on the result? Will the ranking of decision alternatives change as a consequence of this?

In the risk literature there are launched a variety of approaches to investigate the impact of uncertainty in risk analyses – see e.g. (Aven 1992; Aven 2008). Three approaches are described in the following, and exemplified in the case later in this paper, namely:

- Reliability importance measures
- Sensitivity analysis
- Monte Carlo simulations.

The approaches are chosen due to the fact that they represent different ways of addressing the problem requiring different computational efforts.

2.5.1 *Reliability importance measures*

Reliability importance measures can be used in risk analysis to provide information concerning how the system will behave with regards to changes in input parameters. A variety of different measures have been developed. Two classic measures are briefly commented in the following.

Improvement potential

The improvement potential, I^A_i is given by the following equation:

$$I_i^A = h_i - h \qquad (1)$$

where h is the reliability of the system and h_i is the reliability assuming that component i is in the best state (Aven 1992).

I^A_i hence expresses the systems improvement potential if element i in the risk model is replaced with a failure-free element.

Birnbaum's measure

Birnbaum's measure of reliability, I^B_i, is given by the following equation:

$$I_i^B = \frac{\partial h}{\partial p_i} \qquad (2)$$

To compute I^B_i the following formula is often used:

$$I_i^B = h(1_i, p) - h(0_i, p) \qquad (3)$$

where $h(\cdot_i,p) = h(p_1,p_2,..,p_{i-1},\cdot, p_{i+1},..,p_n)$ (Aven 1992). I^B_i expresses the system's sensitivity with regards to changes in element i and is hence a measure for how small changes in parameter i will affect the system.

I^A_i and I^B_i can both provide information concerning the robustness of the obtained solutions and where to look for efficient ways of reducing risk.

2.5.2 *Sensitivity analysis*

Sensitivity analysis is performed using performing repetitive analyses where model parameters are changed, to investigate how the changes affects the risk results and hence get information concerning the robustness of the obtained solution.

Results from reliability importance measures can provide input concerning which parameters to investigate closer in sensitivity analyses.

For the purpose of this paper we only look into single parameter sensitivity analyses, i.e. the effects of changing one parameter at the time.

2.5.3 *Monte Carlo simulations*

In Monte Carlo simulations input parameters are represented by probability distributions, and the results are obtained through calculations sampling from these distributions.

Monte Carlo simulation will require higher modelling efforts compared to sensitivity analyses. For the purpose of this paper we look at Monte Carlo simulations where several input parameters are modelled using probability distributions.

In our case, the expert's judgments are translated into probability distributions which again are the basis for parameter sampling in the simulations.

3 ILLUSTRATIVE CASE

We use a case to illustrate the use of methods to explore uncertainty in QRA as input in electricity distribution decision making. The case is based on a quantitative risk assessment model established in (Nordgård & Solum 2009), being further elaborated for the purpose of this paper. It is emphasised that the case is for illustrative purposes only and that it does not represent the decision basis for a real decision.

For the analysis we use a bow-tie model combining fault tree and event tree analysis.

3.1 *Problem description*

Distribution transformers are located throughout the electricity distribution system, containing typically 150-300 litres of oil depending on their size and rating. The oil which is used in the majority of distribution transformers is considered a potential threat to the environment and to human health. The case evaluates environmental and health risk related to potential oil spill from distribution transformers located within the drainage basin of a drinking water reservoir.

3.2 *Numerical input to the risk modelling*

Due to the fact that it is hard to find statistical material which can support the choice of numerical values to use in the modelling, we have to rely on input from expert judgment. All numerical data used in this case study is hence based on the judgment of company experts and the analyst.

3.3 *Fault tree analysis*

Through discussions with company experts two main failure modes have been identified:

- Oil spill due to degradation of the transformer casing, and
- Oil spill due to strokes of lightning destroying the transformer.

With the first failure mode the transformer may still be working, and the oil spill can be detected by inspections. The second failure mode will destroy the transformer. These two failure modes can be modelled in a fault tree as shown in Figure 2, contributing to the top event; "Oil spill from transformer".

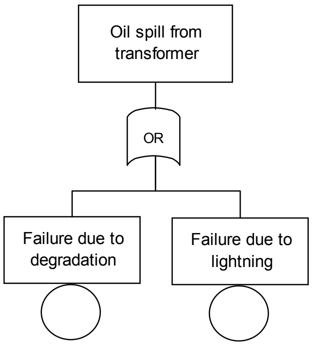

Figure 2 Fault tree - oil spill from transformer.

The following information has been provided by company experts:

- Approximately 1 - 5 out of 1500 transformers have a leakage due to degradation each year.
- Approximately 2 – 3 out of 1500 transformers experience breakage due to lightning strokes each year.

Based on this information the following 'best estimates' are chosen for the fault tree parameters:

- $q_{Degradation} = 2.0 \cdot 10^{-3}$ [events/year]
- $q_{Lightning} = 1.5 \cdot 10^{-3}$ [events/year]

where $q_{Degradation}$ and $q_{Lightning}$ expresses the probabilities for leakage due to casing degradation and lightning respectively.

Assuming independence between the two basic events, the probability of occurrence for the top event is computed according to equation (4):

$$q_{Oil\ spill} = q_{Degrad} + q_{Lightning} - q_{Degrad} \cdot q_{Lightning} \qquad (4)$$

This gives $q_{Oil\ spill} = 0.0035$. Given a case where a company have 25 transformers within a drinking water drainage basin, this gives 0.0875 occurrences of the top event per year - i.e. one can expect the event occurring on average every 11 years.

3.4 *Event tree analysis*

In order to establish the event tree – see Figure 4 – the following barriers are considered, based on discussions with the company experts:

- Whether an oil collector is present
- Whether less than 10 litres of oil leaks
- Whether the transformer is located near a waterway (stream or river) leading directly to the drinking water reservoir.

The amount of oil spilled can not be considered as an ordinary barrier, but rather a statement of possible outcome.

Only substations located on the ground are equipped with oil collectors. The majority of transformers in the area are pole-mounted arrangements, as shown in Figure 3.

Figure 3 Pole-mounted transformer arrangement

The following numerical estimates are chosen for these barriers:

- $q_{Oil\ collector} = 0.9$, i.e only 10 % of the transformers in the area have oil collectors
- $q_{<\ 10\ liters} = 0.8$, i.e. in only 20 % of the cases the oil spill are less than 10 litres
- $q_{Far\ from\ waterway} = 0.6$, i.e. 60 % of the transformers are located near a stream or river leading directly into the drinking water reservoir.

The background for choosing these probability estimates is input from distribution company experts and the analyst.

Based on the previous results from the fault tree analysis, the structure of the event tree in Figure 4 and the probability estimates for the barriers, the results presented in Table 1 are obtained.

We can see that the total expected oil spill within the drainage basin is estimated to be approximately 12.1 litres/years. The most critical event (event 5) – with an oil spill of 250 litres – will expectedly occur every 26 years.

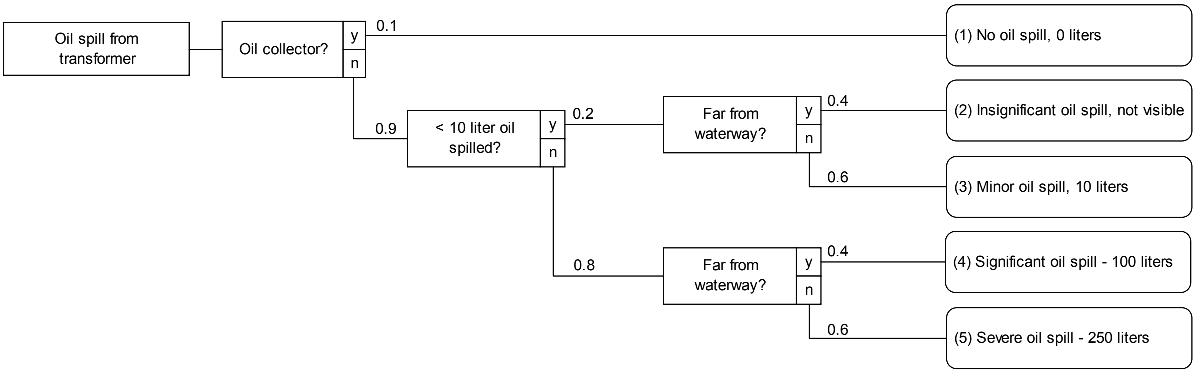

Figure 4 Event tree model for possible outcomes following the start event 'Oil spill from transformer'

Table 1 Results from the event tree analysis

End event	1	2	3	4	5	*Sum*
Oil spill[1)]	0	1	10	100	250	-
Freq.[2)]	0.009	0.006	0.009	0.025	0.038	-
Time[3)],	114	159	106	40	26	-
E(oil spill)[4)]	0.0	0.0	0.1	2.5	9.5	*12.1*

1) Estimated oil spill of the end event, [Litres]
2) Frequency of occurrence of end event *I* [year^{-1}]
3) Expected time between occurrences [years]
4) Expected annual contribution to oil spill from end event *i* [Litres]

3.5 *Investigating uncertainty in input parameters*

The purpose of investigating the effects of uncertain parameters is to illustrate the effect of the changes in the risk analysis model, and to gain understanding and confidence in the risk analysis results.

3.5.1 *Reliability importance measures*

The risk analysis model is first analysed using importance measures to analyze the impact of changes in the input parameters.

Table 2 Calculated reliability importance measures for the input parameters

Model parameter	Improvement potential, I^A_i	Birnbaum measure I^B_i
$q_{Degradation}$	6.9	3448.8
$q_{Lightning}$	5.2	3448.8
$q_{Oil\ collector}$	12.1	5.7
$q_{<10\ litre}$	11.6	6.2
$q_{Far\ from\ waterway}$	5.8	4.1

The improvement potential is the largest for the model parameter $q_{Oil\ collector}$. It should however be noted that the values for the improvement potential are dependent on the values chosen as the base case reference (the value of h in equation (1)).

The Birnbaum measures indicate that the estimated oil spill is clearly most sensitive to the changes in the two fault tree parameters $q_{Degradation}$ and $q_{Lightning}$, but since the failure probabilities here already are very small numbers – the improvement potential is not so large for these parameters.

3.5.2 *Sensitivity analyses*

In order to examine the effects of changing model parameters, sensitivity analyses are performed for low and high estimates for the input parameters. The analyses have been performed by repetitive calculations changing one parameter at the time – seeing how this affects the results. The results for low and high estimates are shown in Table 3, while the 'best-estimate' results are given in Table 1.

Table 3 Results from investigating the effects of uncertainty of input parameters – Low and High estimates

	Parameter estimate		Sum annual oil spill, [Litres]	
	Low	High	Low	High
$q_{Degradation}$	$1.0 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$	8.6	15.5
$q_{Lightning}$	$1.33 \cdot 10^{-3}$	$1.67 \cdot 10^{-3}$	11.5	12.7
$q_{Oil\ collector}$	0.85	0.95	11.4	12.7
$q_{<10\ litres}$	0.6	1.0	9.2	15.0
$q_{Far\ from\ waterway}$	0.5	0.7	11.1	13.0

The variation in results (best estimates from Table 1, and Low/high estimates from Table 3) are illustrated in Figure 5.

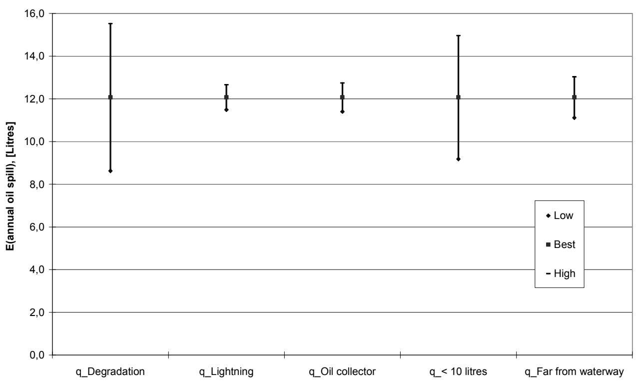

Figure 5 Variation of E(annual oil spill) for low / best / high parameter values

Figure 5 indicates that the largest variation is found for the high/low estimates for the parameters $q_{Degradation}$ and $q_{<10\ litres}$.

3.5.3 *Monte Carlo simulation*

A Monte Carlo simulation model is established to investigate the effect of simultaneous variation of input parameters.

The simulation model is made using triangular distributions for the five input parameters stated in Table 3 with mean values equal to the best estimates and low and high values (Table 3) giving the low and high ends of the probability distributions.

Results from a simulation of estimated annual oil spill are shown in Figure 6. The simulation was made using 1000 iterations sampling from the above given distributions for the five input parameters.

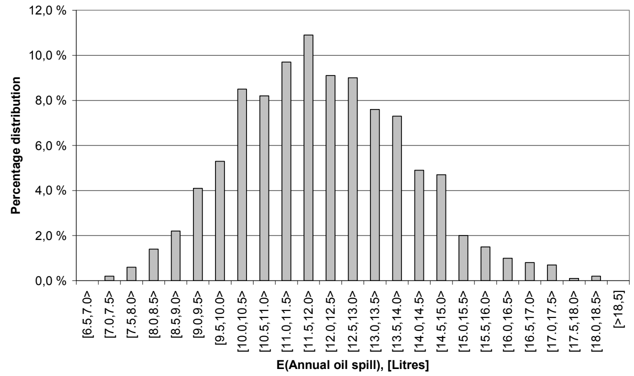

Figure 6 Monte Carlo simulation results of annual oil spill

The centre of gravity for the results corresponds to the expected value we have computed earlier (12.1 litres/year), but we have a widespread variation of results around this value – wider than what is obtained when varying only one parameter at the time, as done in the sensitivity analysis.

We can see from the results that the sensitivity analyses and the Monte Carlo simulations give a more balanced risk picture compared to only the expected values stated in Table 1.

3.5.4 *Evaluation of the initial results*

To evaluate the results – we use a taxonomy proposed in (Wessberg et al. 2008) to evaluate the consequences of potential accidental emissions. The taxonomy uses three consequence categories for ground water / water intake:

- Moderate. No harm to water intake
- Extensive: Water intake is temporarily prevented
- Serious: Water intake is prevented for the long-term

Table 4 shows the risk categorisation.

Table 4 Risk matrix – risk categorisation – *based on Table 3 (Wessberg et al. 2008)*

	Moderate	Extensive	Serious
5 - More than once a month	II	I	I
4 - More than once a year	II	I	I
3 - More than once in 10 years	III	II	I
2 - Once in a lifetime[1)]	IV	III	II
1 - Situation is known[2)]	IV	IV	IV

1) The lifetime of the industrial site

2) It has happened sometimes somewhere

The risk categories in Table 4 are classified as follows (Wessberg et al. 2008):

- I: Risk elimination actions must be started immediately
- II: Risk reduction needed. Proposals for actions as soon as possible.
- III: Proposals for actions to risk reduction should be given within a year.
- IV: No actions needed

The estimated expected consequence for our case is regarded to be in the categories *Moderate* to *Extensive,* while the probability of occurrence is in categories 2 – 3. The investigated uncertainty in the risk results supports the choice of these categories.

We can draw the conclusion that the risk can not be considered unconditionally acceptable, and proposals for risk reduction should be considered – but that there is no need for immediate action.

3.6 *Decision alternatives*

To address this problem further the following decision alternatives have been identified for the risk analysis as means to reduce risk:

- Alternative 1: Leave as is. (basis alternative)
- Alternative 2: Redesign of transformer arrangements to include oil-collectors.
- Alternative 3: Relocation of transformers – location further away from waterways.
- Alternative 4: Redesign of transformer earthing system – making it less exposed to lightning strokes.
- Alternative 5: Replace transformers with new design with environmentally friendly insulating oil. This alternative is regarded to eliminate the negative consequences from oil spill.

The model parameters chosen for the alternatives are stated in Table 5, and the expected values of annual oil spill for the chosen alternatives are illustrated in Figure 7.

Table 5 Model parameters used for the different alternatives*

	Parameter estimates			
	Alt. 1	Alt. 2	Alt. 3	Alt. 4
$q_{Degradatio}$	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$q_{Lightning}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
$q_{Oil\ collector}$	0.9	0.1	0.9	0.9
$q_{< 10\ litre\ oil}$	0.8	0.8	0.8	0.8
$q_{Far\ from\ waterway}$	0.6	0.6	0.1	0.6

* *Alternative 5 eliminates the environmental impact of the transformer oil. The system reliability parameters for alternative 5 remain unchanged – i.e. equal to alternative 1.*

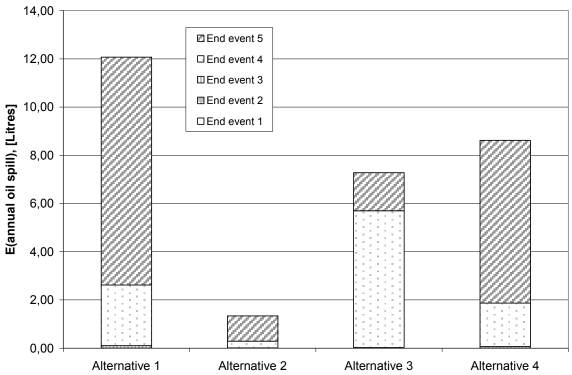

Figure 7 E(annual oil emissions) for Alternatives 1-4 with partial contribution from the different end events.

The different alternatives can also be investigated with sensitivity analyses too see how the changes in parameter estimates will affect the results.

Figure 8 shows an example on how changes in one parameter – in this case $q_{Lightning}$ – influences the estimated expected annual oil spill.

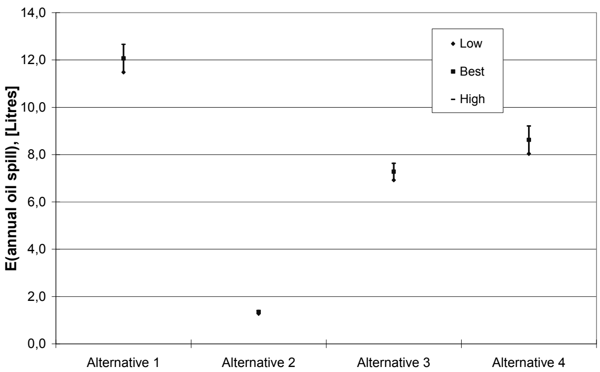

Figure 8 E(annual oil emissions) for Alternatives 1-4 for low, best and high estimates of $q_{Lightning}$.

The analysis clearly indicates that alternative 2 is the most efficient one with regards to risk reduction.

3.7 *Comments to the case*

The case illustrates some possibilities of exploring uncertainty in input parameters in a quantitative risk assessment model.

The purpose of performing such analyses should be to provide the decision maker with information concerning the robustness of his or hers risk analysis results. It should also be emphasised that the risk analyses will provide indicative rather than absolute answers as illustrated by the results from the case.

The risk analysis results should further be brought into a decision making process, where other aspects such as cost, reputational impact, etc. should also be included. The uncertainty in the risk analysis results should also be taken into account in the final decision making process.

The final decision making process is not further elaborated in this paper. An example on how such decision support can be performed can e.g. be found in (Catrinu & Nordgård 2009).

4 CONCLUDING REMARKS

This paper has presented three different methods for how uncertainty in input parameters can be explored in quantitative risk analysis and how the results can be used to provide decision support.

For the purpose of providing decision support in relatively simple QRA models in electricity distribution system asset management, sensitivity analysis will provide an efficient way to give useful information with a relatively low computational effort. Reliability importance measures can be used to give direction of where to look for risk reducing measures, but it should be accompanied with sensitivity analysis to illustrate the effect of the changed parameters. Monte Carlo simulation will give a broader risk picture, but it will demand more sophisticated modelling, and the results provided will not give significantly more information compared to sensitivity analyses.

What should be emphasised when exploring uncertainty in QRA is highlighting the fact that risk analysis results are not objective, crisp values – but uncertain figures which are more or less sensitive to changes in model input parameters.

We see that the results based on 'best estimates' will represent only part of the risk picture which the decision maker should be aware of.

In practical application, a realistic ambition is to use risk analysis to increase the understanding of the risk problem, and to provide input to risk-informed decisions. It should be kept in mind that also other input than risk analyses are relevant in the decision making context. The risk analysis should hence never be the sole basis for making decisions, but rather contribute to making decisions risk-informed (Apostolakis 2004). Exploring uncertainty is an important part of this task.

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Paper IV. “**Using life curves as input to quantitative risk assessment in electricity distribution system asset management**”.

Dag Eirik Nordgård, Thomas Welte and Jørn Heggset.

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Paper IV

Is not included due to copyright

Paper V. “**Risk assessment methods applied to electricity distribution system asset management**”.

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Paper V

Risk assessment methods applied to electricity distribution system asset management

D.E. Nordgård
Norwegian University of Science and Technology, Trondheim, Norway

K. Sand
SINTEF Energy Research, Trondheim, Norway

I. Wangensteen
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: This paper highlights some aspects of the many facets of electricity distribution system risk assessment – describing the different risk consequence categories which are relevant in the whole risk picture with regards to their characteristics, their type of impact and applicable risk analysis methods. The paper illustrates that distribution system asset management constitutes of a variety of more or less conflicting objectives – and that there is no single risk assessment method which cover all the different aspects of distribution system risk.

1 INTRODUCTION

Electricity distribution systems are a vital infrastructure in modern society. The management of such systems consists of balancing cost, performance and risk – taking into account different aspects such as economic performance, quality of supply, safety and environmental impacts (Brown & Spare 2004; Sand et al. 2007). These aspects often constitute conflicting objectives in the decision making processes.

Electricity distribution is by definition a so-called natural monopoly – i.e. it is not socio-economic efficient to build competing parallel infrastructures to provide this service. In order to prevent abuse of monopoly power, the industry is subject to extensive regulation from authorities.

During the last two decades substantial changes have taken place in the electricity distribution sectors worldwide, changing it from generally being a protected business to being exposed to efficiency requirements and benchmarking through the monopoly regulation of electricity distribution. The process has lead to efficiency improvements throughout the business. Motivated by these efficiency requirements, the electricity distribution companies have intensified their efforts of creating more efficient ways of managing their business, trying to be on the competitive edge as measured by the regulatory authorities benchmarking practices (NVE 2007).

On main trend is that the electricity distribution companies have been increasingly focusing on the concept of *asset management* as guiding principle for performing their business – see e.g. (Kostic 2003; Brown & Spare 2004; Tor & Shahidehpour 2006). The area of asset management has emerged from different industries which all have in common the importance of an infrastructure of physical assets for performing their business Asset management covers widely – encompassing a multitude of aspects in distribution system planning and operation (BSI 2004a). Risk management is important among these aspects, being a part of asset management decision support methodology.

There is an increasing awareness among electricity distribution companies on developing holistic strategies for asset management, seeking solutions where all relevant risks consequence categories are being sufficiently taken care of – see e.g. (Nordgård et al. 2007; Istad et al. 2008).

This paper highlights major trends in the application of risk analysis in electricity distribution system asset management.

The paper first gives a description of the concept of asset management, pointing out how this is applied in the electricity distribution sector. It further states how risk assessment is included in electricity distribution system asset management, and how risk assessment methods are used to address various risks. Different risk consequence categories which are relevant for electricity distribution are listed, and each of them is described both in terms of their characteristics, their type of impact and what methods are applicable for analyzing them. Finally some concluding remarks are made concerning using risk-based approaches in distribution system asset management.

2 ELECTRICITY DISTRIBUTION SYSTEM ASSET MANAGEMENT

The electricity distribution sector has been increasingly focusing on the concept of asset management as guiding principle for performing business.

For example, the UK regulator, Ofgem, has explicitly encouraged the distribution companies to get certified according to the publicly available specification PAS 55 "Asset Management" (BSI 2004a; BSI 2004b), in order to establish a adequate level of competence in asset management within the distribution companies, to assure long term asset risk management and establish greater clarity of the policies and processes that underpin the investment decisions of network companies (Williams et al. 2007).

The concept of asset management covers (at least) two aspects; the management of the physical infrastructure, and the management of the organizational aspects. In this paper we focus on the first of these two aspects, namely the infrastructure management.

A very general definition of asset management is given in specification PAS 55-1 (BSI 2004a): *"Asset management is simply the optimum way of managing assets to achieve a desired and sustainable outcome"*.

The importance of risk management (as a means of avoiding undesired events) is highlighted in the more formal definition of asset management: *"systematic and coordinated activities and practices through which an organization optimally manages its assets, and their associated performance, risk and expenditure over their lifecycle [..]"* (BSI 2004a).

This definition emphasizes the lifecycle aspects of cost, performance and risk exposure – where performance is a measure of what is achieved, while risk exposure represents foresight – looking into potential future outcomes, with the aim to avoid undesired events.

From this definition we can see that risk management is well integrated in the asset management scheme. The principle of continuous process improvement is also a guiding star of asset management, integrating the different aspects of a sound asset management in a *plan-act-review-improve* circle. Risk assessment as a part of the asset management process of continual improvement, is illustrated in Figure 1 (BSI 2004b).

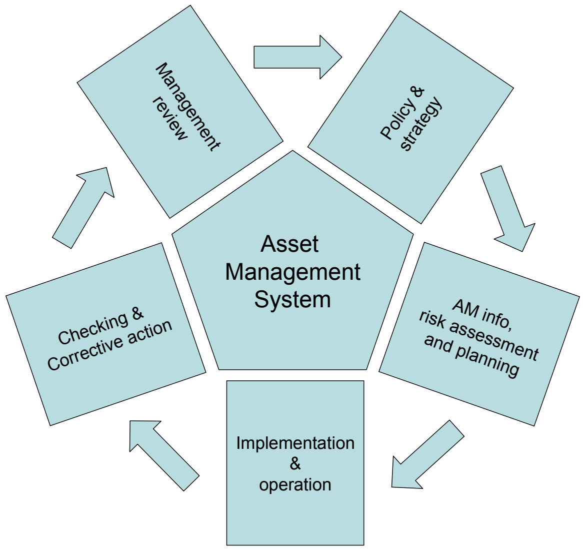

Figure 1. Asset management system elements – Continual improvement – based on (BSI 2004b).

3 RISK AND RISK ASSESSMENT IN ELECTRICITY DISTRIBUTION SYSTEM ASSET MANAGEMENT

The understanding and management of risk are key issues for distribution companies in their asset management approaches.

Much work within risk management in distribution systems have focused on the aspects of reliability, see e.g. (Fangxing & Brown 2004; Bertling et al. 2005). This focus is understandable, since it is surely an important feature of the product delivered by the electricity distribution infrastructure, being a focal area for regulatory authorities in many countries (Eurelectric 2005).

However, electricity distribution companies are also concerned with other important decision criteria representing relevant risks for their business. This typically involves more *intangible* risks such as safety, environmental impact and company reputation.

In contrast to the numerous methodologies developed for reliability calculations and decision support (Billinton et al. 2001), one will find less application of structured analyses to support decisions concerning other risks, even though they represent an important motivation for decisions taken in electricity distribution systems. Some examples can yet be found – see e.g. (Hamoud et al. 2007; Nordgård 2008).

3.1 *Distribution system risk*

The electricity distribution companies acknowledge that there are many facets to the risk picture that they face. In (Sand et al. 2007) a study is presented identifying different aspects of the electricity distribution company risks. The consequence categories are shown in Table 1.

All of these risks are not applicable to every decision situation in the distribution companies, but the consequence categories constitute a whole of risk assessments that should be kept in mind when addressing distribution company risk.

Table 1 Different consequence categories in distribution system asset management – based on (Sand et al. 2007).

Risk consequence categories
- Economic risk
- Safety risk
- Environmental risk
- Quality of supply risk
- Reputational risk
- Vulnerability risk
- Regulatory risk

In the following chapters we look further into each of these risk consequence categories. The presentation is based on the authors' knowledge and experience regarding the application of risk assessment methods in electricity distribution – first and foremost among Norwegian distribution companies. Some of the risks are well defined with respect to risk analysis methods, while others have less history of being subject to structured risk assessment.

3.2 *Taxonomy for categorisation*

To describe the various risks we have chosen a taxonomy consisting of descriptions of their:

- Risk characteristics,
- The type of impact the risks will have, and
- The type(s) of risk assessment methods which are applicable.

3.2.1 *Risk characteristics*

The characteristics of each risk consequence category are provided as a high level description, not going into detail.

Some important aspects of each risk are highlighted as to why this is an area of concern for the distribution companies.

3.2.2 *The degree of impact of risk*

The different risk consequence categories have their differences with regards to the extent of their impact. In our review of the risk consequence categories, three types of impact are used:

- Local impact – denoting impact coming from dedicated components causing "concentrated" accidents or incidents.
- System impact – denoting impact occurs when failure in component(s) or sub-systems provides widespread impact affecting extensive parts of the distribution system.
- Corporate impact – denoting risks which impact on foundation for performing the business. This may be as a consequence of a preceding local or system impact, or due to a independent incident

3.2.3 *Categories of methods for risk analysis*

In (Aven 2008) three main categories of risk assessment methods are presented, as stated in Table 2. These categories are used to provide a generic grouping of the different categories of methods for risk analysis.

The three categories represent an increasing degree of formalism and modelling sophistication. The choice of method depends on the purpose of the study, the need for resolution, input data available, etc.

Table 2 Categories of methods for risk analysis – grouping based on (Aven 2008)

Category	Type of analysis	Description	Example of methods
Simplified risk analysis	Qualitative	Informal procedures that analyses risk using e.g. brainstorming sessions and group discussions.	- Coarse risk analyses - Brainstorming sessions
Standard risk analysis	Qualitative or quantitative	More formalized procedures in which recognized risk analysis methods are used. Risk matrices are often used to present the results.	- Risk analysis assisted by HAZOP - Risk matrices - Job safety analysis
Model-based risk analysis	Primarily quantitative	Formal methods using e.g. event tree analysis (ETA) and fault tree analysis (FTA) are used to calculate risk.	- Fault tree analysis - Event tree analysis - Reliability analyses - Bayesian networks - Electrical system simulation - Benchmarking methods

Table 2 indicates that the more sophisticated the method gets, it will inevitably get more specialised. For model-based risk analyses there are a variety of analysis methods which can be used to analyse specific risk scenarios in detail.

The need for data - and its resolution - is also increasing significantly from the simplified risk analysis methods to the model-based ones.

4 DESCRIPTION OF VARIOUS ASPECTS OF RISK VALID FOR DISTRIBUTION SYSTEMS

In the following chapters the risk consequence categories listed in Table 1 are described closer, using the taxonomy presented in chapter 3.2.

4.1 *Economic risk*

4.1.1 *Characteristics of economic risk*

Economic risk is related to the potential loss of money – i.e. through higher cost than anticipated or through loss of income. Potential economic loss influences all aspects of electricity distribution system asset management.

Before the introduction of income cap regulation it was sufficient to analyse investments with respect to costs (because of cost coverage). In an income cap (or price cap) regulatory regime distribution companies also evaluate projects with respect to income effects, since the difference between the allowed income (stated by the regulatory authorities) and the total costs (opex + capex) constitute the company profit.

Hence, the main economic planning objective for the distribution companies is to minimize all relevant costs while meeting relevant restrictions.

The Norwegian regulator, NVE, has in their regulations given incentives for the companies to minimise the expected net present value of the following cost elements (NVE 2007):

- Investment cost (including reinvestment and renewal costs)
- Operating and maintenance costs - including utility repair and damage costs
- Cost of electrical losses
- Customer outage costs i.e. costs of energy not supplied (CENS)
- Congestion costs.

Uncertainty – and hence risk – is related to all of these cost elements, some more than others.

4.1.2 *Impact of economic risk*

Economic risks will typically have impact on corporate level.

4.1.3 *Methods applicable for analysing economic risk*

To analyse economic risk net present value (NPV) analyses are widely used – preferably accompanied with sensitivity analyses to investigate the effect of variation of input parameters. In some case risk matrices can be used to present and visualise the economic risk being part of a decision basis.

Input to the economic analyses can be provided through by other model based analyses, e.g. reliability analysis, load development forecasts, etc.

4.2 *Quality of supply risk*

4.2.1 *Characteristics of quality of supply risk*

The distribution companies are being increasingly subjected to regulatory regimes that explicitly take into account the quality of supply to the consumers (Eurelectric 2005).

One example is the Norwegian regulation scheme of Quality adjusted revenue caps, where the network companies' revenue caps are adjusted in accordance with the customers' interruption costs (Langset et al. 2001).

In addition to regulation of the interruption, there are also standards regulating the technical phenomena of quality of supply (CENELEC 2007).

4.2.2 *Impact of Quality of supply risk*

Quality of supply may impact both on local and system level – depending on the type of problem, its' size etc.

4.2.3 *Methods applicable for analysing Quality of supply risk*

Costs related to power supply interruption is a part of the economical risk – and hence NPV calculations are a methods also here. Model based methods for estimation of expected reliability and interruption conditions may provide input data for the NPV calculations.

To estimate potential impact on the technical quality of supply phenomena, various electrical system simulations may be utilised, e.g. load flow analyses, short circuit analyses, etc. The power system physical laws are well defined and the system therefore relatively easy to model and simulate.

It should be noted that depending on the regulatory regime, quality of supply phenomena might be dealt with in a purely economical way and hence contribute as an economical risk scenario. The cost of energy not supplied is one example – penalties when exceeding contract values another. So, care should be taken to avoid double counting of risk impact.

4.3 *Vulnerability risk*

4.3.1 *Characteristics of vulnerability risk*

Vulnerability is a characteristic of a system's inadequate ability to withstand an unwanted event, limit the consequences, and recover and stabilize after the occurrence of the event (Doorman et al. 2006).

The electricity supply is essential for the quality of everyday life, for the safety of people and for the economy. Vulnerability of the electric power networks therefore affects the society as a whole.

In our context vulnerability risk is used to describe high impact, low probability events that might have such a widespread effect on important societal functions.

Norms regarding the security of electricity supply considers the supply to end-users irrespective of the causes for a power system of not being able to ensure a sufficient security of supply.

4.3.2 *Impact of vulnerability risk*

By its nature vulnerability risk have widespread impact on system level and also on corporate level.

4.3.3 *Methods applicable for analysing vulnerability risk*

To analyse vulnerability risk various system simulations are applicable; e.g. contingency analyses, dynamic analyses etc. Other – more generic – model-based risk analysis methods are also applicable (e.g. fault tree and/or event tree. Simplified and standard risk analyses methods (brainstorming, plotting in risk matrices) can also be used for more coarse analyses of vulnerability. Risk matrices can be used as a tool to visualise the results.

4.4 *Safety risk*

4.4.1 *Characteristics of safety risk*

Safety considerations are often decisive for actions in the distribution system. The risk covers both occupational and third party safety.

For third party safety the concern is mainly coming from the potential accidental touching of live electrical system parts, e.g. the conductor wires of overhead lines.

Occupational safety is in addition covering various aspects related to the construction, operation and decommissioning of components in the distribution system.

4.4.2 *Impact of safety risk*

Safety risk will in most cases have a local impact, affecting people being relatively close to the scene of the incident or accident. Severe incidents or accidents affecting safety may also have a corporate impact.

4.4.3 *Methods applicable for analysing safety risk*

For analysing safety risk simplified and / or standard risk analyses methods are mostly applied – e.g. through performing brainstorming sessions to identify undesired events, and illustrating the results in risk matrices. Job safety analysis is yet another relevant approach used in the operational phase of asset management.

4.5 *Environmental risk*

4.5.1 *Characteristics of environmental risk*

Environmental hazards emerging from distribution companies are mainly related to pollution (e.g. emissions of oil from oil-filled components, SF_6-gas leakages, etc). Visual pollution – e.g. from overhead lines crossing through nature - is also a factor, together with electric and magnetic fields emerging from distribution system components.

Another potential environmental risk aspect is that pollution-abatement equipment such as pumps and filters often depend on electricity. Power outages might hence have environmental effects.

4.5.2 *Impact of environmental risk*

Environmental risk related to distribution system components can both have a local impact, affecting the sites being close to the scene of the incident / accident, and a global impact, since some pollutants have a global impact e.g. emissions the green house gas SF_6 used in various types of switchgear.

4.5.3 *Methods applicable for analysing environmental risk*

To analyse environmental risk simplified or standard risk analyses are most often applied. Risk matrices are often used to present and visualise the risk analysis results.

4.6 *Reputational risk*

4.6.1 *Characteristics of reputational risk*

Goodwill among various stakeholders are important aspects of running a business and this is also valid for distribution companies. They are aware of their reputation in order to improve or maintain it, and also to brand other business areas that the companies might be directly involved in –e.g. broadband services, alarm services, installation services etc.

Reputational risk will often be closely linked to other risk – such as quality of supply, safety, environmental risk, vulnerability and so on. The companies' performance on the other risk areas may hence affect the reputational risk.

4.6.2 *Impact of reputational risk*

Reputational risk related to distribution system components can both have a local impact, affecting only people being close to the scene of the incident. Depending on the type of incident or accident the reputational risk may also have corporate impact.

4.6.3 *Methods applicable for analysing reputational risk*

To the extent that reputational risk are formally analysed, this is done through simplified or standard risk analyses, using risk matrices to present and visualise the results.

4.7 *Regulatory risk*

4.7.1 *Characteristics of regulatory risk*

Due to the fact that electricity distribution companies are natural monopolies, they are being subject to extensive regulation from the authorities. Changes in the regulatory framework – e.g. due to political decisions, new regulatory models, etc. – can have large impact on companies.

If the regulatory regime is not well designed, a socio-economic beneficial project (i.e. a project with positive net present value of the cost minimisation objective function) might give a negative net present value income-wise and hence not be realised. Regulatory risk might play an important role when assessing strategies, and might for example lead to a reinvestment and maintenance adverse philosophy.

Regulation concerning certain component design may also enforce replacements, etc.

4.7.2 *Impact of regulatory risk*

Regulatory risk will by its nature have impact on corporate level.

4.7.3 *Methods applicable for analysing regulatory risk*

To analyse regulatory risk, all types of risk analyses is applicable; from simplified standard risk analyses, to highly detailed analyses using simulations to investigate the effects of various future scenarios on the company situation in changing regulatory frameworks - e.g. through data envelopment analysis (DEA), etc.

4.8 *Summary*

The survey of various distribution company risks in the previous chapters illustrate a variety of different aspects which are included in the total risk picture, and the variety of applicable approaches to analyse these risks.

Table 3 summarises the results of the different consequence categories, indicating the predominant attributes of the various risk consequence categories. What can be seen from the table is that there is no single method or approach which can be said to cover all aspects in one common risk analysis framework. It will rather encourage the use of many different approaches to analyse distribution system risk, depending on the type of problem.

5 THE MULTI CRITERIA NATURE OF RISK MANAGEMENT IN ASSET MANAGEMENT

The different risks listed in the chapters 3 and 4, all constitute parts of the rather complicated jig-saw puzzle of distribution system asset management, and should all to be kept in mind in a holistic asset management framework.

For a majority of asset management decisions there will not be relevant to include all risk aspects into the decision, but for a great deal we need to take into account more than one risk (e.g. safety and economic performance) and these risk may often be counteractive, meaning that the optimum solution for one risk will not be favourable for other(s), and vice versa. In a decision making context we will therefore have to deal with compromises between various aspects representing expected performance and risks.

5.1 *Decision problem example*

As an illustration we can consider the reinvestment of a MV overhead line, including rebuilding of pole-mounted MV/LV transformers to arrangements on the ground.

Figure 2 Example: Reinvestment of MV overhead line

The potential reinvestment will have risk related to cost occurring during the building process, and the future impact on the allowed company income is subject to regulatory risk. A new overhead line with ground mounted transformers will represent a reduction in occupational safety risk (due to less need for climbing), but leave the third party safety risk relatively unchanged. Environmental risk due to potential transformer oil emissions can be reduced, if rebuilding transformed on the ground with oil collectors, while the visual pollution remain unchanged. The reinvestments impact on vulnerability risk is neglectable.

This simple case illustrates the multi-criteria nature of such decision problems.

Table 3 Summary of risk consequence categories, their predominant impact and risk analysis methods.

	Risk impact			Risk analysis methods			
Risk consequence categories	Local	System	Corporate	Simplified	Standard	Model-based	Methods used
Economic / financial risk			+		+	+	NPV-analyses
Safety risk	+		+	+	+		Brainstorming, Risk matrices
Environmental risk	+	(+)	+	+	+		Coarse risk analysis
Quality of supply risk	+	+		+	+	+	NPV-analyses, Power system Analysis
Reputational risk	+		+	+	+		Coarse risk analysis Risk matrices
Vulnerability risk		+	+	+	+	+	Coarse risk analysis Risk matrices, Power system analysis
Regulatory risk			+		+	+	Coarse risk analysis Risk matrices, Simulation (e.g. data envelopment analysis)

5.2 *The challenge of optimizing*

To perform a formal optimization we have to be able to express some objective function with its restrictions, and to find *the solution* which minimizes (or maximises) this function.

To do this it is necessary to formulate each of the risks in the same terms (usually money or utility value) – see e.g. (Vatn 1998).

Monetisation raises some ethical questions – e.g. on putting value on safety and loss of life, and whether it is representative for the companies and society's attitude towards risk to use the expected values when dealing with safety risks or environmental risks, or if we should be more risk averse for such consequence categories.

For decision support purposes it can also be questioned if the purpose of a decision support tool is to compute the answer of the decision or whether its' role is to provide input for the decision maker to use in his or her own considerations.

In the process of utilising risk assessment in a more structured manner in electricity distribution, it is our opinion that one should try to establish better analysis approaches for each of the risk aspects before jumping to the aggregation of risks into on common measure with the aim to perform a full optimization – emphasising to provide decision support rather than decision optimization.

There are however multi-criteria decision methods which can contribute to bridging the gap towards aggregating partial results into a common decision framework – see e.g. (Catrinu & Nordgård 2009). This is not further elaborated in this paper.

6 CONCLUDING REMARKS

This paper highlights some aspects of the many facets of distribution system risk assessment – characterising the different consequence categories which are relevant in the whole risk picture.

The application of holistic risk analyses in distribution system asset management is relatively new – and the companies have to get more experience using risk assessment approaches in their distribution system asset management.

The purpose of risk assessment should be to analyse uncertainty about future outcomes in a structured and traceable manner and to provide better foundations for making asset management decisions.

To obtain a structured approach to analyze the various aspects of distribution company risk, there is a need for strengthening the distribution companies with regards to:

- Competence
- Methods and tools
- Input data.

All of these aspects need to be elaborated further in the years to come

It is the authors' opinion that it is not realistic to obtain one unified risk assessment method which can cover all the different risks, but rather to develop analyses for the different risks, each of them constituting a part of the total decision basis.

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Paper VI. “**A framework for risk-informed decision support in electricity distribution companies utilizing input from quantitative risk assessment**”.

Dag Eirik Nordgård.

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Paper VI

A Framework for Risk-Informed Decision Support in Electricity Distribution Companies utilizing input from Quantitative Risk Assessment

Dag Eirik Nordgård

Department of Electrical Power Engineering
Norwegian University of Science and Technology, Norway
N-7491 Trondheim
Norway

Dag.Eirik.Nordgard@elkraft.ntnu.no
Telephone: +47 73 59 76 63
Mobile: +47 93 22 16 79

Abstract:

Electricity distribution companies are to an increasing extent using risk assessment methods in their asset management practices. This paper presents an overall framework for risk-informed decision sup-port where simplified risk analysis methods are used for initial risk assessment, and quantitative risk analysis methods are used to perform more in-depth studies for selected problems. Quantitative risk assessment methods are far more laborious compared to simplified analyses, so it is important that such analyses are performed only to a limited number of risk problems.

Keywords:

Risk analysis, risk-informed decision support, asset management, quantitative risk assessment

1. INTRODUCTION

Electricity distribution companies throughout the world are adopting the principles of *asset management* as guidance for how to optimally handle their infrastructures, see e.g. [1-3].

In the core of asset management lies decisions concerning balancing the aspects of cost, performance and risk, in order to ensure an optimal utilization of the physical assets, [4, 5]. This gives the motivation for developing methods for risk analysis, with the aim to support asset management decision making.

Risk analysis for electricity distribution has often focused on reliability analyses, analyzing how the system behaves with regards to interruptions in the electricity supply, see e.g. [6-8]. Reliability is surely an important feature of the product delivered by the electricity distribution infrastructure, being a focal area for regulatory authorities in many countries [9]. However, electricity distribution companies are also concerned with other important decision criteria which represent relevant risks for their business. These risks typically involve safety, environmental impact and company reputation, see e.g. [10-12]. In this paper we refer to such risks as *intangible risks*. The impact of intangible risks on decisions is especially important on medium and low voltage distribution levels, where the consequences of system reliability failures are not as large and widespread as on higher voltage levels. Hence, there is a need to include the analysis of these risks in the decision making.

This paper describes an overall framework for risk-informed decision making in electricity distribution asset management. The basic steps of the framework is coherent with general risk management principles, as described in e.g. [11, 13-15], but in addition the framework emphasizes the use of quantitative risk analysis (QRA) methods for in-depth studies of selected risk problems. Candidates for more thorough risk analysis can be critical undesired events, undesired events with potentially large consequences, or undesired events where the uncertainty in the initial estimate is high.

Section 2 gives a background description of risk, risk analysis and risk management, referring to general risk management concepts found in the literature. Then the proposed framework is presented in section 3, before the framework is exemplified using an asset management decision case, shown in section 4. The paper concludes with some remarks concerning the practical use of the framework.

2. BACKGROUND

2.1 Risk

Risk and risk analysis is relevant in most decision situations since we by assessing risk seek to look into the future, aiming to use this providence to make good decisions.
Kaplan [16] defines that when we ask "What is the risk?" for a given process or activity, we really ask three questions:

- What can go wrong?
- How likely is that to happen?
- If it does happen, what are the consequences?

For the purpose of this paper this definition of risk is used, and the three questions will form the basis of risk analysis.

2.2 Methods for risk analysis

Numerous methods have been developed for risk analysis, and they represent different levels of detail and resolution. In [14] three main categories of risk analysis methods are presented, as shown in Table 1.

Table 1 Categories of methods for risk analysis – grouping based on [1]

Category	**Type of analysis**	**Example of methods**
Simplified risk analysis	Qualitative	- Coarse risk analyses - Brainstorming sessions
Standard risk analysis	Qualitative or quantitative	- Risk analysis assisted by HAZOP - Risk matrices - Job safety analysis
Model-based risk analysis	Primarily quantitative	- Fault tree analysis - Event tree analysis - Reliability analyses - Bayesian networks - Electrical system simulation - Benchmarking methods

The three categories represent an increasing degree of formalism and modelling sophistication. Which method to choose will depend on the purpose of the analysis, the need for resolution, etc. In the framework described in section 3 a differentiation of risk analysis methods is proposed, based on the problem at hand.

2.3 General frameworks for risk management

The literature provides several general frameworks which give an overview of risk and risk management.

In [15], five steps are listed presenting the essentials of the risk assessment and management process:

- Risk identification
- Risk modelling, quantification and measurement
- Risk evaluation
- Risk acceptance and avoidance
- Risk management.

In [14] three high-level elements are stated:

- Planning
- Risk assessment (execution)
- Risk treatment (use)

[13] also addresses risk management, and Figure 1 illustrates a conceptual risk management process based on structure and terminology presented in this reference.

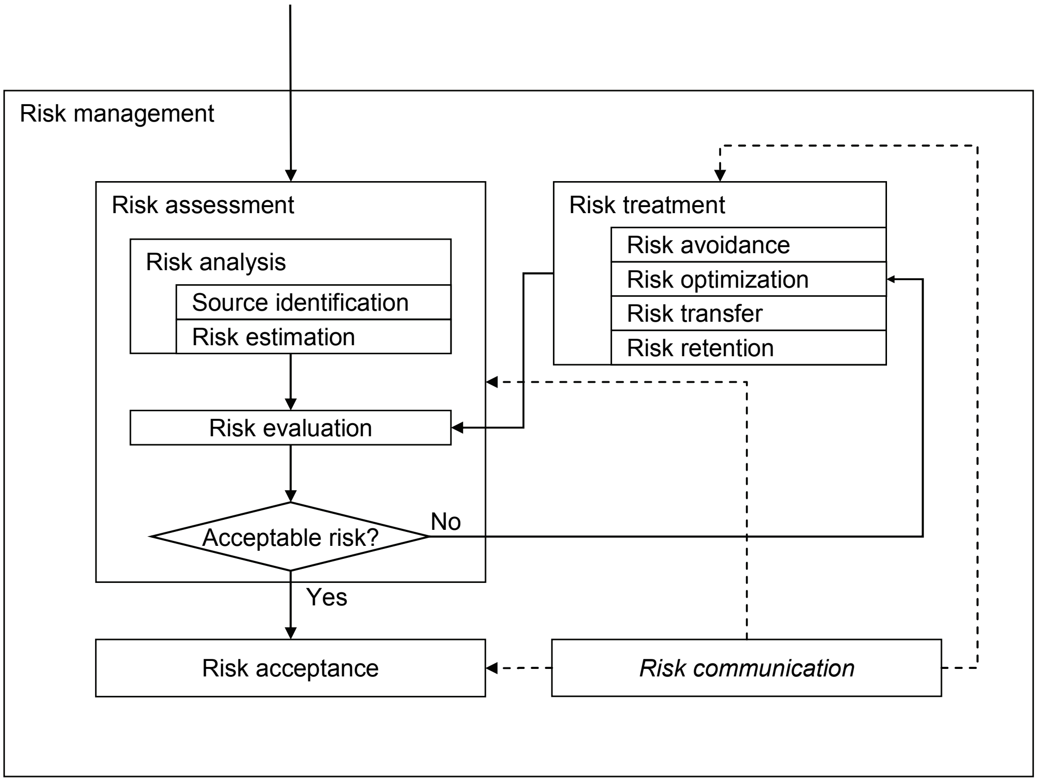

Figure 1 Risk management process – based on structure and terminology from (ISO/IEC, 2002).

All of these general frameworks encompass the same basic principles, even though emphasis is somewhat different in the different sources. But all frameworks deal with risk identification, risk analysis and risk evaluation – leading towards risk-informed decision.

2.4 Risk in electricity distribution system asset management

Electricity distribution companies face a variety of risks, with potential impact on many consequence categories. In [11] and [12] the following risk consequence categories are presented as being the most relevant for distribution companies:

- Economy
- Safety issues (for employees and the public)
- Reputation
- Environmental issues
- Quality of supply

- Fulfilment of contractual obligations.

In order to address these risk consequence categories, different methods are used in electricity distribution companies. In [12] a summary of risk analysis methods in use is presented – spanning from simplified analyses to advanced model-based approaches.
In the framework proposed in this paper, simplified risk analysis, supported by risk matrices, is used to perform an initial risk analysis and to provide a mapping of risks. For selected problems these initial results can be complemented using QRA.
The steps of the framework are described in the section 3, followed by a case in section 4. The case is based on an example of risk-informed decision making in a distribution company, based on [17].

3. A FRAMEWORK FOR RISK-INFORMED DECISION SUPPORT UTILIZING QUANTITATIVE RISK ASSESSMENT

In order to structure the process of using risk assessment as input to decision making, an overall framework for decision support is proposed, as shown in Figure 2.
Compared to the general frameworks for risk-management described in section 2, the framework emphasizes the use of QRA to analyse selected risk problems. The selection of what problems to analyse with QRA will be based on a qualitative evaluation of the results from the initial risk analysis process, but also from other decision inputs – e.g. from economic analyses.

The steps of the proposed framework are described in the following.

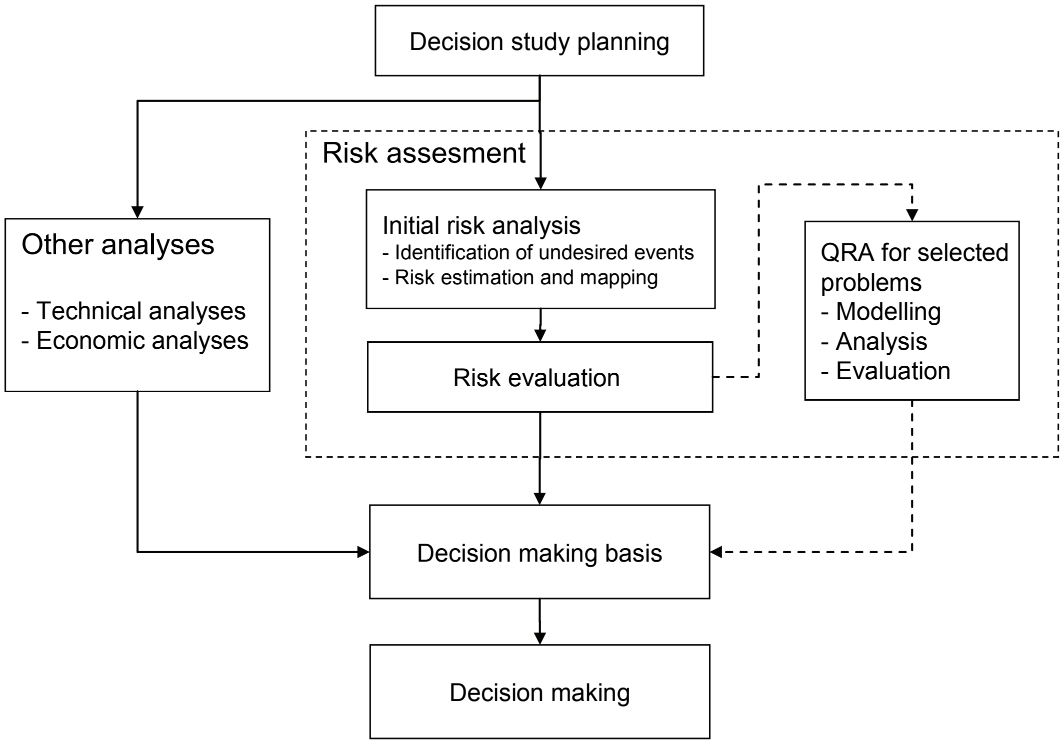

Figure 2 Proposed framework for risk-informed decision support in electricity distribution system asset management

3.1 Decision study planning

The formulation of the problem is a key factor for all decision making, because the purpose of the analysis needs to be clearly formulated. Some other aspects which must be addressed in this phase are [11]:

- Delimitation of system boundaries
- Identification of stakeholders, and
- Stating objectives and decision criteria.

In addition it is important to state the time horizon for the analyses, and to clarify the terminology to be used.

3.2 Risk assessment

The purpose of the risk assessment is to establish a risk picture for the decision maker(s). This can be done through the following steps.

3.2.1 Initial risk analysis

Risk analysis deals with finding answers to Kaplan's triplet of questions listed in section 2.1. This is done through identifying undesired events and estimating probabilities and consequences for these events.

To perform the initial risk analysis, the use of simplified risk analysis methods – in combination with risk matrices - is proposed, in order to gain a overview of the risks with minimum use of resources, see e.g. [18].

Identification of undesired events

The first, but very important step of the risk analysis is the identification of potential undesired events; i.e. answering the question "What can go wrong"?

In this part of the framework the aim is to identify relevant sources of risk and to pinpoint undesired events which might be caused by these sources.

Input to this task can be:

- Expert knowledge
- Results from inspections
- Data from databases
- Results from previous analyses

Experience shows that concerning analysis of intangible risks it is very limited what we can find in databases [18, 19], e.g. due to the fact that statistics simply do not exist. Previous analyses are also few in numbers so far, since there is limited experience available when it comes to performing risk analyses for intangible risks. Expert judgement and results from inspections will hence in most cases be the available sources for information.

The output from the identification will be a listing a potential undesired events.

Risk estimation and mapping

The risk estimation includes assessing probability and consequence estimates for the undesired events [13] – i.e. answering question two and three of Kaplan's triplet. To map and visualise the risk results, risk matrices should be used. The mapping in risk matrices should be done with respect to each of the consequence categories found relevant for the decision. Typical examples of such consequence categories can be economic impact, safety, environmental impact and reputational impact, see e.g. [18, 20].

Potential sources of data for such estimates will be the same as for the sources to identify the undesired events, and also in this context will expert judgment be of great importance. Probability and consequence estimates can be on qualitative or semi-quantitative form, e.g. "high", "medium", "low" or "1 – 10 occurrences per year", see e.g. [18, 19].

3.2.2 Risk evaluation

Risk evaluation deals with determining the significance of risks [13], and judging whether the risks are acceptable or not.

Even though the risk analysis will provide a risk picture with a classification of undesired events, the key question is still: What is acceptable risk?

The literature treats this problem in numerous ways. In e.g. [21] it is concluded that acceptable-risk problems are decision problems, requiring choices among alternatives, assuming that no risk is unconditionally acceptable, but that the acceptability of a given risk will depend on what are the alternatives. The decision is dependant on the values and beliefs of the decision maker(s), among also other factors. It is therefore impossible to give a universal answer to what is acceptable risk. For the purpose of this work, Fischhoff et al.'s [21] conclusion is used as a basis; that there are no universal acceptance threshold for risk acceptance, and that it is decision context dependent.

Guidance can however be found in what previously has been accepted for similar risks or through comparison with other risks in society. This is however not a trivial task. For the purpose of this thesis, it can be concluded that the acceptability of a risk will be for the decision maker(s) to decide.

The initial risk mapping will in many cases provide sufficient information concerning the risk picture, and there will be no need for more detailed analyses, see e.g. [18].

The risk evaluation may however reveal potential risks which may call for a more in-depth investigation – e.g. by using quantitative risk assessment (QRA) methods. The identification of candidates for QRA will be based on a qualitative evaluation performed by the decision maker. Candidates for a more thorough investigation may include:

- Undesired events which are found critical
- Undesired events with potentially large consequences
- Undesired events where the uncertainty of our initial estimates is high
- Evaluation of alternative solutions for risks considered unacceptable.

The motivation for performing a QRA is to provide better understanding of the problem and a better basis for decision making.

3.2.3 Quantitative risk assessment for selected problems

There are several methods for quantitative risks analyses available. The QRA methods have in common that they require a mathematical representation of the system, and that they result in numerical risk estimates for a given risk, expressed in e.g. PLL (Potential loss of life), FAR (fatal accident rate), litres of oil spilt during one year, kg SF_6 gas accidentally released into the atmosphere, or expected annual cost.

The process of using QRA includes:

- Describing the system – e.g. relevant barriers, maintenance actions, etc
- Establishing models representing causal relations
- Estimating model parameters
- Calculating and presenting results
- Dialogue and discussion with relevant stakeholders regarding model assumptions, numerical inputs and results.

The choice of QRA method depends on the problem at hand, the data availability, etc. For cases concerning analysing intangible risks – see [17, 22-25] bow-tie models (combining fault tree and event tree analysis) and Bayesian networks have been tested.

3.3 Other analyses

While being in the context of electricity distribution risk analysis, it is still important to bear in mind that risk analysis results are only parts of the decision basis, and that it should not be the sole basis for decision making, see e.g. [26]. Other aspects and analysis results will contribute to the total decision basis, e.g. load flow analyses, short circuit analyses, reliability analysis (covering risks related to loss of electricity supply) results from economic analyses, company policies, etc.

3.4 Decision making basis

The decision making will typically have to take into account more than one decision criterion, hence we face multi-criteria decisions – see e.g. [27-29].
The basis for the asset manager to make her or his decisions will constitute of several pieces of information for each analysis; e.g. risk analysis results for more than one consequence category, technical analyses (load flow analysis, short circuit analysis) and results from economical analyses.

3.5 Decision making

In the end, the final decision making is the task of the decision maker(s) – i.e. judge what is acceptable risk, what is the better alternative, how to control the identified risks, etc.
The decisions can be performed on a qualitative basis or by using more formal decision aid tools as support. Examples of multi-criteria decision making methods are discussed and illustrated in [28, 29].
The decision making process may also include iterative risk analyses to investigate potential solutions to risk problems, through considering the effects of various risk mitigating measures. Throughout the process it is also important to focus on the aspect of risk communication to relevant stakeholders.

4. CASE STUDY

In this chapter the proposed framework is applied to a decision making case to illustrate the procedure. The case is based on application of risk-informed decision making in a distribution company, as described in [17] and [25].

4.1 Decision study planning

The case addresses risk-informed decision making related to pole mounted transformers in a distribution company. The motivation for the analysis was to provide basis for maintenance

strategy making and reinvestment planning. The stakeholders were the asset manager(s) in the company.
The risk consequence categories which were considered relevant were economy, safety, environmental impact and reputational impact.

4.2 Risk assessment

4.2.1 Initial risk analysis

Table 2 shows an excerpt of undesired events identified for pole mounted MV/LV distribution transformers, and the undesired events' impact on the four risk consequence categories.
The undesired events were identified through guided discussions with distribution company experts.

Table 2 Case: undesired events identified for pole mounted MV/LV distribution transformers and their impact on the consequence categories.

Undesired events ***Number and description***	**Economy**	**Safety**	**Environment**	**Reputation**
1. Oil leakage from transformer			+	+
2. Wrong voltage to customer du to earth fault	+			+
3. Fall from pole mounted platform		+		+
4. Short-circuit on transformer	+			
5. Internal fault in transformer	+			+
6. Third party climbing and assessing the platform		+		+

The following qualitative probability and consequence scales were used for risk estimation, based on [19]:

P5 – Highly Probable	C5 – Catastrophic
P4 – Very Probable	C4 – Serious
P3 – Probable	C3 – Medium
P2 – Less probable	C2 – Small
P1 – Improbable	C1 – Negligible

Each of the undesired events was assigned a probability and a consequence estimate based on input from company experts. The results are visualised in the risk matrix in Table 3.

Table 3 Case: Plotting of the undesired events in risk matrix

	C1	C2	C3	C4	C5
P5					
P4					
P3					
P2		1(rep.)	1(env.)		
P1		2(ec./rep.) 5(ec./rep.)	3(rep.) 6(rep.) 4(ec.)	3(saf.) 6(saf.)	

Abbreviations: ec. = Economy, saf.= Safety,
env. = Environment, rep. = Reputation.

4.2.2 Risk evaluation

In the case most of the undesired events were not considered to be critical, and that they could be controlled through standard maintenance activities. The decision makers have however identified uncertainty concerning undesired event # 1 – *Oil leakage from transformer* - and the risk related to potential oil spill from transformers located within the drainage basin of drinking water reservoirs. The potential impact of such events and the uncertainty concerning the nature of the undesired event called for a closer investigation.

4.2.3 Quantitative risk assessment for a selected problem

For the purpose of the case a bow-tie model was chosen to perform the quantitative risk analysis. A bow-tie model is a high-level modelling for risk analysis – combining the results from fault tree analysis and event tree analysis in order to explicitly establish the cause/effect relations related to an undesired event, see e.g. [30, 31].

Problem description

MV/LV transformers are located throughout the distribution system, and they typically contain 150-300 litres of oil depending on their MVA rating. The case evaluates environmental risk related to oil spill from distribution transformers located within the drainage basin of drinking water reservoirs.

Statistical material which can provide valid support in choosing numerical values to use in the modelling was not found. All numerical data used in the case were therefore based on the judgment of company experts and the analyst.

Fault tree analysis

Two main failure modes were identified:

- Oil spill due to degradation of the transformer casing
- Oil spill due to strokes of lightning destroying the transformer.

The two failure modes was modelled in a fault tree as shown in Figure 3, contributing to the top event; "*Oil spill from transformer*".

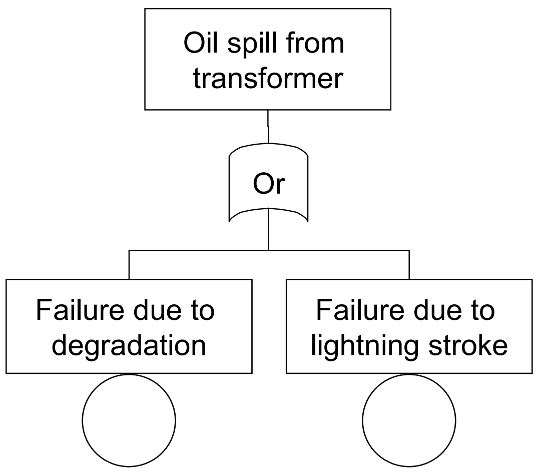

Figure 3 Fault tree for the undesired event "Oil spill from transformer"

The following information was provided by company experts:

- Approximately 1 - 5 out of 1500 transformers have a leakage due to degradation each year.
- Approximately 2 – 3 out of 1500 transformers experience breakage due to lightning strokes each year.

Based on this the following estimates are chosen for the fault tree parameters:

- $q_{Degradation} = 2.0 \cdot 10^{-3}$ [events/year]
- $q_{Lightning} = 1.5 \cdot 10^{-3}$ [events/year]

where $q_{Degradation}$ and $q_{Lightning}$ expresses the probabilities for leakage due to casing degradation and lightning respectively. Assuming independence between the two basic events, the probability of occurrence for the top event is computed according to equation (1):

$$q_{Oil\ spill} = q_{Degradation} + q_{Lightning} - q_{Degradation} \cdot q_{Lightning} \quad (1)$$

This gives $q_{Oil\ spill} = 0.0035$. Given a case where a company have 25 transformers within a drinking water drainage basin, this gives 0.0875 occurrences of the top event per year - i.e. one can expect the event occurring on average every 11 years.

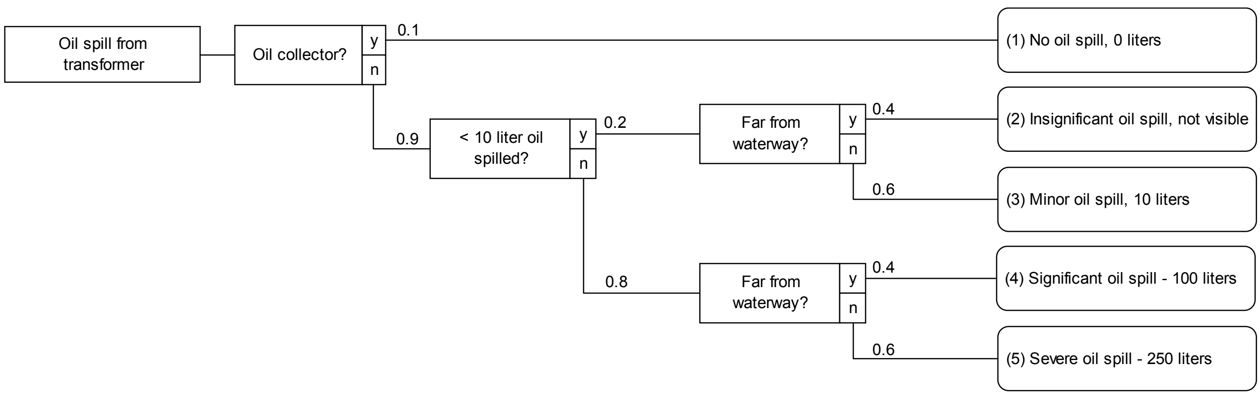

Figure 4 Event tree for the undesired event "Oil spill from transformer" – based on (Nordgård, 2009a*)*

Event tree analysis

In order to establish the event tree – see Figure 4 – the following barriers are considered, based on discussions with the company experts:

- Presence of an oil collector
- Less than 10 liters of oil will leak
- If the transformer is located near a waterway (stream or river) leading directly to the drinking water reservoir.

The amount of oil spilled can not be considered as an ordinary barrier, but rather a statement of possible outcome.

Only substations located on the ground are equipped with oil collectors. The majority of transformers in the area are pole-mounted arrangements.

The following numerical estimates are chosen for these barriers:

- $q_{Oil\ collector}$ = 0.9, i.e. only 10 % of the trans-formers in the area have oil collectors
- $q_{< 10\ liters}$ = 0.8, i.e. in only 20 % of the cases the oil spill are less than 10 litres
- $q_{Far\ from\ waterway}$ = 0.6, i.e. 60 % of the trans-formers are located near a stream or river leading directly into the drinking water reservoir.

The probability estimates were based on input from distribution company experts and the analyst.

Based on the results from the fault tree analysis, the structure of the event tree and the probability estimates of the barriers, the results presented in Table 4 are obtained.

We can see that the total expected oil spill within the drainage basin is estimated to be approximately 12.1 litres/years. The most critical event (event 5) – with an oil spill of 250 litres – will according to the estimates on average occur every 26 years.

Table 4 Case: Results from event tree analysis

End event	**1**	**2**	**3**	**4**	**5**	**Sum**
Oil spill [1)]	0	1	10	100	250	-
Freq.[2)]	.009	.006	.009	.025	.038	-
Time[3)],	114	159	106	40	26	-
E(oil spill) [4)]	0.0	0.0	0.1	2.5	9.5	*12.1*

1) Estimated oil spill of the end event, [Litres]
2) Frequency of occurrence of end event *I* [$year^{-1}$]
3) Expected time between occurrences [years]
4) Expected annual contribution to oil spill from end event *i* [Litres]

In order to explore the effects of uncertainty concerning the numerical estimates chosen for modelling, various sensitivity analyses should be performed. This is done in [25]. It is beyond the scope of this paper to go further into the details of this.

The analysis of alternatives to meet potential unacceptable risks can also be supported by the bow-tie model. This can give comparable quantitative estimates on the effects of various risk mitigating measures.

4.3 Other analyses

Other aspects and analysis which will contribute to the decision basis for the case are, e.g. load flow analyses to establish the loading of transformers, short circuit analyses, reliability analysis, and economic figures concerning costs of various possible measures.

4.4 Decision making basis

The decision making basis will consist of input from the various analyses, constituting the parts of a multi-criteria decision. The basis for the asset manager to make decisions will hence constitute of several pieces of information.

4.5 Decision making

This part of the process can be aided by using decision support methods and tools, but in the end, the final decision is the task of the decision maker(s). Factors which influence the decision are the values and beliefs of the decision maker, company policies, available alternatives, etc. This paper will not go into the detail of the decision making.

5. CONCLUDING REMARKS

Asset management decision making is in many aspects a jig-saw puzzle, with parts supplied from different sources. To solve the puzzle, there is a need to use methods for risk-informed decision support.

This paper describes an overall framework for risk-informed asset management decision making. This is done through the use of simplified risk analysis methods for initial risk assessment, and quantitative risk analysis methods to perform more in-depth studies for selected problems. Due the fact that QRA methods are far more laborious compared to simplified analyses, it is important that such analyses are limited to a small number of problems.

We should keep in mind that the basis for risk analysis is uncertainty about future outcomes. This uncertainty can be explored by performing risk analyses, but it can never be eliminated. The aim of risk analysis should therefore be to contribute to increase problem understanding and to make robust decisions which can deal with future risk in a good manner, rather than providing the “right” answer.

The results from risk analyses will – together with results from other analyses – constitute a more solid the basis for making decisions.

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Paper VII. "**Risk communication and perception challenges in electricity distribution maintenance and reinvestment management**".

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Paper VII

RISK COMMUNICATION AND PERCEPTION CHALLENGES IN ELECTRICITY DISTRIBUTION MAINTENANCE AND REINVESTMENT MANAGEMENT

Dag Eirik Nordgård
Norwegian University of Technology and Science
Dag.E.Nordgard@elkraft.ntnu.no

ABSTRACT
The principles of risk management are widely recognised as useful when making maintenance and reinvestment decisions in electricity distribution systems. But when doing this in practice, the distribution companies may encounter challenges. This paper describes the areas of risk communication and perception, highlighting some aspects concerning terminology and psychology which one should be aware of as important parts of risk management as a whole.

INTRODUCTION

The electricity distribution system is to a large degree an already existing infrastructure - most of it being built during the last 50 years. Hence, the distribution companies are now facing the challenges of managing a generally ageing infrastructure. This gives maintenance and reinvestments more prominent positions than before.

There is now an increasing trend among distribution companies on developing maintenance strategies where different aspects of risk are included in a holistic way [1-3]. The risk aspects typically involve safety, environmental concerns, company reputation, quality of supply and economy.

The principles of risk management is widely recognised as intuitively right when making decisions concerning maintenance and reinvestments (see e.g. [4]), but when doing risk analyses in practice, the distribution companies encounter challenges. These challenges are related to assessing as well as communicating and perceiving the various aspects of risk, and may include:

- Choosing methods for modelling and analysis
- Estimating parameters to be used in the models
- Understanding the risk analysis and it's results, including it's uncertainties
- Presenting results to various stakeholders
- Understanding responses from various stakeholders

Several of these challenges are related to risk communication and perception, and will typically involve multiple stakeholders - both inside and outside the distribution companies.

This paper describes some general characteristics of risk communication and risk perception to illustrate why this is a non-trivial task. It further points out how this can be relevant and applicable to the setting of electricity distribution companies, and shows a list for illustrating some relevant cases applicable to electricity distribution.

RISK COMMUNICATION AS PART OF RISK MANAGEMENT

There are different ways of defining and structuring the aspects of risk management. For this paper, the structure and terminology proposed in [5] is used as the basis for the presentation. *Risk communication* is regarded as a part of the risk management framework and is defined as *exchange or sharing of information about risk between the decision-maker and other stakeholders* [5].

Risk communication will typically not be an isolated task, and in order to obtain good communication about risk, the interaction and dialog between risk analyst(s), decision-maker(s) and other stakeholders should be an integrated part of the whole of risk management, reaching into the processes of *risk assessment*, *risk treatment* and *risk acceptance* as illustrated in Figure 1.

Risk communication will also be an important part of the final decision making process, where also other relevant inputs to the decision are incorporated.

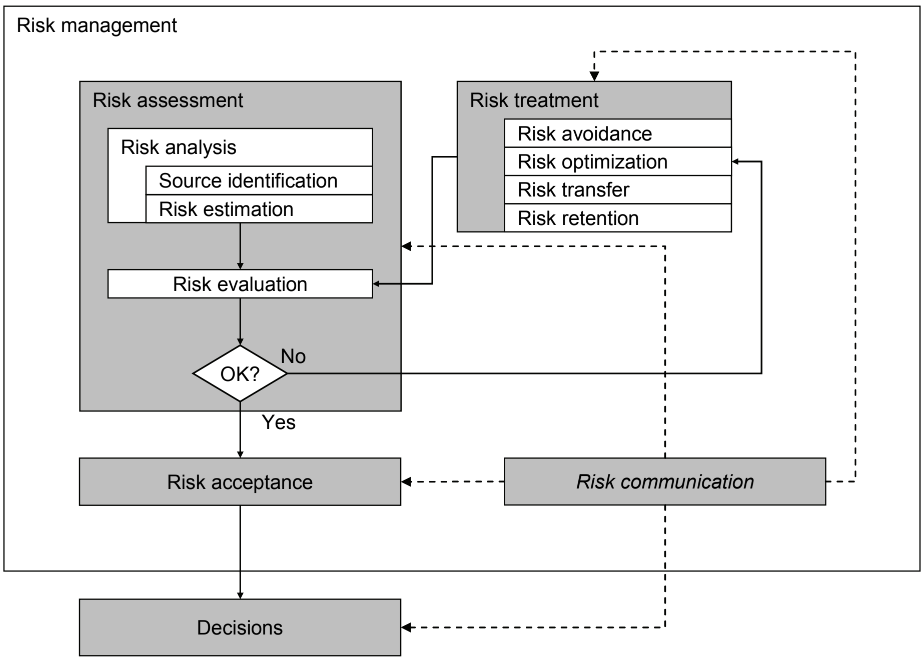

Figure 1. Risk management process flowchart – based on Risk Management terms from [5]

There exist several general models for information and communication processes. One simple model is illustrated in Figure 2, where four main steps of communication from a sender ("source") to a receiver ("Destination") are shown.

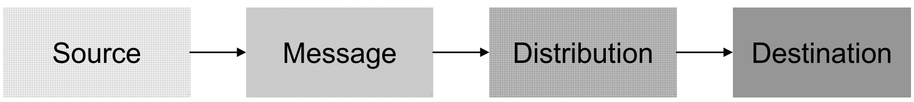

Figure 2. Simple communication model – based on [6]

Along the communication chain one will encounter challenges regarding getting the message through to the receiver as intended by the sender. The sender and the receiver will typically be different stakeholders in a risk related situation. What the receiver hears, and how he or she reacts, will depend on the person's background, current situation, relation to the risk problem, etc.

There are some specific points which are of interest when looking into the challenges of risk communication, and in the following chapters two of these challenges are elaborated, namely:

- The terminology challenge of risk, and
- The psychological challenge of risk perception.

RISK - A TERMINOLOGY CHALLENGE

Dangers will always be present in life, and there is no way that these can be totally eliminated. The chance of such dangers or hazards appearing is what we may call *risk*. Risk is generally a concept that denotes a potential negative impact that may arise from some present process or future event.

For analytical purposes this can be defined as risk being *the combination of the probability of an event and its consequence* – see e.g. [5] – or even the product of these two quantities. In technical analyses this definition is quite widespread.

But when communicating with people having a different background one can encounter problems regarding even this basic terminology regarding *risk*. There are a number of more or less accepted definitions and use of *risk* from a number of different fields of application – covering both formal and informal uses of the term. In [7] an overview is given on how the term *risk* is used in everyday language and across disciplines. A summary of this is given in Table 1.

Table 1. Definitions and usage of the term risk (based on [7])

Risk (usage / definition)	Description / Example of usage
1: An unwanted event which may or may not occur.	'Lung cancer is one of the major risks that affect smokers.'
2: The cause of an unwanted event which may or may not occur	'Smoking is by far the most important health risk in industrialized countries.' (The unwanted event implicitly referred to here is a disease caused by smoking.).
3: The probability of an unwanted event which may or may not occur	"The risk that a smoker's life is shortened by a smoking-related disease is about 50%."
4: The statistical expectation value of an unwanted event which may or may not occur.	The expected value of a possible negative event is the product of its probability and some measure of its severity. Today this is the standard technical meaning of the term "risk" in many disciplines (first introduced by the Reactor Safety Study, WASH-1400 in 1975).
5: The fact that a decision is made under conditions of known probabilities	"Decision under risk" as opposed to "Decision under uncertainty" – which refers to decisions made under conditions of unknown probabilities.

Even among risk analysts there is difficulty in converging on a common definition of the term. The following anecdote from [8] illustrates the complexity to achieve a cross disciplinary definition of *risk*:

> *"One of the first initiatives from the Society for Risk Analysis was to establish a committee to define the word risk. The committee laboured for 4 years and then gave up, saying in its final report, that maybe it is better not to define risk and let each author define it in his own way, emphasizing that each should explain clearly what way that is."*

It is therefore important to be explicit about what understanding of *risk* is used when performing and documenting risk assessment, and one should also be aware of the possible different interpretations of the term when presenting results from risk analyses.

The terminology challenge will presumably be most relevant when communicating risk and risk analysis results to receivers who do not have a technical background, but even when sending the message to engineers one should be cautious to specify what is meant by the term.

RISK – A PSYCHOLOGICAL CHALLENGE

Risk perception is the judgement that people (often referred to as 'stakeholders') make about the characteristics and severity of a given risk. Their perception of risk will further influence on the way they act upon risk information. The acceptability of a given risk lies in the "eyes of the beholder" – and is hence stakeholder-dependant [9, 10].

There are several aspects which affect a stakeholder's perception of risk. In the pioneer work of Chauncey Starr [10] two main aspects are pointed out, being *voluntariness* of being exposed to a risk, and which *benefits* are perceived from the risk exposure - stating that it is much easier to accept risk which is of your own choice, rather than risk which is felt forced upon you; and that it is much easier to accept a risk of which you benefit yourself. Starr also pointed out the influence of the number of people affected by a risk, and the magnitude of a risk event.

Much work has been done within this area during the last four decades, and much focus has been on communication of risk in the interface between risk analysts and the general public [11], but risk perception is relevant for also other stakeholder interfaces [12].

In the case of electricity distribution there are also other very relevant communication interfaces – e.g. risk communication between the distribution company and governmental bodies, risk communication as input to decision makers within the company and risk communication between asset manager and internal or external service providers.

In [13] a comprehensive summary is given over aspects which may play a role in a stakeholder's perception of risk. Some main findings of this summary are shown in Table 2.

Table 2. Aspects affecting stakeholders' perception of risk, based on [13].

Risk aspect	Description
Voluntariness	Risks from activities considered to be involuntary or imposed (e.g., exposure to chemicals from a industrial facility) are judged to be greater, and are therefore less readily accepted, than risks from activities that are seen to be voluntary (e.g., smoking or sunbathing)
Controllability	Risks from activities viewed as under the control of others (e.g., releases of toxic chemicals by industrial facilities) are judged to be greater, and are less readily accepted, than those from activities that appear to be under the control of the individual (e.g., driving a car).
Familiarity	Risks from activities viewed as unfamiliar (e.g. chemicals or radiation from waste disposal sites) are judged to be greater than risks from activities viewed as familiar (such as household work).
Fairness	Risks from activities believed to be unfair or to involve unfair processes (e.g., inequities related to the siting of industrial facilities) are judged to be greater than risks from fair activities (e.g., vaccinations).
Benefits	Risks from activities that seem to have unclear, questionable, or diffused personal or economic benefits (e.g., waste disposal facilities) are judged to be greater than risks from activities that have clear benefits (jobs, monetary benefits, automobile driving).
Catastrophic potential	Risks from activities viewed as having the potential to cause a significant number of deaths and injuries grouped in time and space (e.g., airplane accidents) are judged to be greater than risks from activities that cause deaths and injuries scattered or random in time and space (e.g., automobile accidents).
Understanding	Poorly understood risks (such as the health effects of long-term exposure to low doses of toxic chemicals or radiation) are judged to be greater than risks that are well understood or self-explanatory (such as pedestrian accidents or slipping on ice).
Uncertainty	Risks from activities that are relatively unknown or that pose uncertain risks (e.g., risks from genetic engineering) are judged to be greater than risks from activities that appear to be well known to science (e.g., actuarial risk data related to automobile accidents).
Delayed effects	Risks from activities that may have delayed effects (e.g., long periods of time between exposure and adverse health effects) are judged to be greater than risks from activities viewed as having immediate effects (e.g., poisonings).
Effects on children	Risks from activities that appear to put children specifically at risk (e.g., milk contaminated with toxic chemicals, pregnant women exposed to radiation or toxic chemicals) are judged to be greater than risks from activities that do not (e.g., workplace accidents).
Victim identity	Risks from activities that produce identifiable victims (e.g., a child who falls down a well or a miner trapped in a mine) are judged to be greater than risks from activities that produce statistical victims (e.g., statistical profiles of automobile accident victims).
Dread	Risks from activities that evoke fear, terror or anxiety (e.g., exposure to cancer-causing agents or AIDS) are judged to be greater than risks from activities that do not arouse such feelings or emotions (e.g., common colds and household accidents).
Trust	Risks associated with institutions or organizations lacking in trust and credibility (e.g., industries with poor environmental track records) are judged to be greater than risks from activities associated with those that are trustworthy and credible.
Media attention	Risks from activities that receive considerable media coverage (e.g., accidents at nuclear power plants) are judged to be greater than risks from activities that receive little attention (e.g., on-the-job accidents).
Accident history	Risks from activities with a history of major accidents or frequent minor accidents (e.g., leaks at waste disposal facilities) are judged to be greater than risks from those with little or no such history (e.g., recombinant DNA experimentation).
Personal stake	Risks from activities viewed by people to place them or their families directly at risk (e.g., living near a waste disposal site) are judged to be greater than risks from activities that appear to pose no direct or personal threat (e.g., disposal of waste in remote areas).
Human vs. natural origin	Risks generated by human action, failure or incompetence (e.g., accidents caused by inadequate safeguards or operator errors) are judged to be greater than risks believed to be caused by nature (e.g., exposure to geological radon or cosmic rays).

Research and experience have shown that there is no ”right” answer on how to handle the these challenges related to risk perception, but it is important the distribution companies to be aware of the terminological and psychological mechanisms which may affect an efficient communication of risk.

RISK COMMUNICATION AND PERCEPTION WITHIN ELECTRICITY DISTRIBUTION

The electricity distribution business involves the interaction between different stakeholders with different roles to play. There are therefore multiple stakeholder interfaces where risk communication aspects are of interest.

The stakeholders hold roles both inside and outside the distribution companies themselves. A schematic mapping of stakeholders and stakeholder interfaces is given in Figure 3, showing the roles of the company asset management (in the centre of the figure) with other influencing stakeholders surrounding.

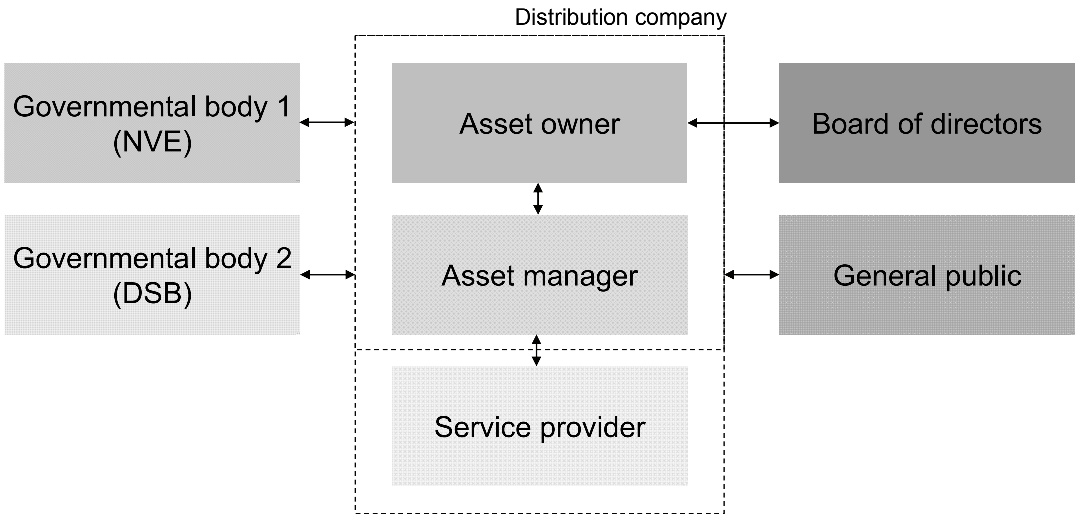

Figure 3. Electricity distribution business: Schematic mapping of internal and external stakeholders and stakeholder interfaces.

Outside the core of the distribution company there are governmental bodies which the company has to relate to, the board of directors which require risk informed information, and the general public – including the customers of the company and people affected someway or another by the distribution system infrastructure.

The stakeholder interfaces can roughly be divided into two main categories of risk communication:

- Risk communication to decision makers, *and*
- Risk communication to the public.

Table 3. Categorisation of stakeholder interfaces.

Categories of risk communication	Stakeholder interface
Risk communication to decision makers	Asset manager / Asset owner to board Asset manager to asset owner Asset manager / Asset owner to governmental body
Risk communication to the public	Asset manager to service provider Distribution company to general public

The aspects influencing risk perception given in Table 2 are most representative for the communication interface between the distribution company and the general public, and between asset manager and service provider.

For the other stakeholder interfaces it is more relevant to focus on aspects related to risk assessment methods, choices of input parameters, treatment of uncertainty, etc. [12].

In [11] (p. 156-157) Bier makes the following remark concerning the aspects of communicating risk analysis to decision makers:

> *"Little research has been done on effective methods of communicating risk analysis results to decision-makers. With the advent of risk-informed decision-making, decision makers are increasingly being asked to take highly technical risk analysis results into account in their decisions. Therefore, it is important to pilot-test risk communication messages and approaches whenever possible, and to share the results of such evaluations as widely as possible to disseminate knowledge about how to most effectively communicate risk information to support regulatory decision-making."*

This stresses the importance on further work on risk communication to (and between) company decision makers, acknowledging that this holds somewhat other challenges compared to what is experienced in risk communication to the public.

EXAMPLES OF RISK COMMUNICATION TOPICS

In Table 4, a brief list is given of some risk related topics which are relevant for some of the different stakeholder interfaces shown in Figure 3. The listing is not intended as a complete and unabridged listing of risk topics, but rather to present some examples which are seen as relevant to illustrate the diversity of risk challenges within distribution system asset management.

Table 4. Stakeholder interfaces and examples of risk communication topics.

Stakeholder interface	**Risk communication topics**	**Keywords**
Distribution company vs. general public	*Electro-magnetic fields near power system components*	- Electromagnetic fields themselves are invisible - Children are believed to be more vulnerable to the risk - Uncertainty about risk, but severe consequences (fearing increased chance of leukemia among children being exposed to high levels of electromagnetic fields)
	Large scale interruptions of electricity supply	- The society is highly dependent on a reliable electricity supply - Large consequences (economic, safety, reputation) when occurring, but (relatively) rare events - Minimize what risk to what cost
Asset manager vs. service provider	*Communicating the identified risks and providing two-way communication*	- The decision of "acceptable risk" done by the asset manager, while first line working experience with the ageing infrastructure is felt by the employees of the service provider - Communication of the risk assessments which provide the background for the priorities in the grid, and to provide feed-back regarding observations of the component condition
Distribution Company vs. governmental bodies	*Providing common understanding regarding risk assessment and management*	- Regulations for the distribution business have changed, emphasizing the use of risk assessment as input to decisions - Changing the way of thinking and acting from a black-and-white rule regulation to a risk informed shades-of-gray application, is a challenge partly still unsolved
Asset manager / owner vs. company board	*Presenting risk assessment results*	- The board is responsible for the performance of the company, requiring information concerning different risk aspects of the electricity distribution business - Asset managers and/or the asset owner provides such information - A challenge to provide compact information to the board presenting risk evaluations and solutions (including uncertainty) - e.g. regarding larger reinvestments in the grid
Asset managers vs. asset owner	*Performing and presenting risk assessment*	- To provide a bi-directional flow of information concerning strategic risk priorities of the company, and to show how these priorities are used in risk informed decisions - Challenges regarding uncertainty assessment regarding priorities in the grid e.g. evaluation of the technical condition of assets, etc. - People in different positions may have different backgrounds (education, working experience) – which may be a challenge with regards to understanding the challenges related to assessing distribution system risk

CONCLUDING REMARKS

The paper points out some aspects which are relevant when discussing risk perception and communication within the electricity distribution sector. Some are more prominent than others, but they are all parts of a rather complex jig-saw puzzle of holistic distribution system asset management.

Until recently the concept of risk has only to a minor degree been systematically applied in the electricity distribution industry – and when applied it has been in the strictly 'technical sense', where risk is set equal to probability of an event multiplied with consequence of the event. Risk assessment in electricity distribution has also further been focused on mainly one aspect of risk, namely the reliability of the system (and hence the quality of supply).

Risk communication and perception have many aspects which go beyond the "technical" risk analysis, including how the basic understanding of risks differs between stakeholders, and how results are interpreted and used. The purpose of addressing this challenge is to build understanding and knowledge, and to contribute to a better foundation for risk management within the industry as a whole.

Risk management is about tackling the inherent uncertainties related to future outcomes, and in this context is imperative to understand the nature of risk and risk analysis, with its possibilities and limitations. It is important to acknowledge that risk analysis will not provide the "correct objective answer", as all risk analyses will provide subjective results – i.e. the results are dependent on the choices made by the analyst regarding modeling, input parameters, numerical values used, etc. Risk analysis results should therefore rather be used to contribute to a risk informed decision basis where other aspects of risk management – e.g. risk communication and perception – are included.

Future work within this field of application should encompass these different areas, but special emphasis should be put on the topics of risk communication between stakeholders within the distribution companies – and hence risk communication to (and between) company decision makers, [12], acknowledging that this includes somewhat other challenges compared to what is experienced in risk communication to the public.

The challenge is (at least) two-fold; as it calls for increased knowledge and skills among both *analysts performing risk assessment* and *the receivers of the results* for such analyses.

Incorporating risk communication as an integrated part of the decision making process is a key feature for further work, with the aim to provide the distribution companies with tools for making better decisions.

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