CHALMERS
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Risk Management in the Infrastructure Industry

How Can Monte Carlo Simulations Reduce Uncertainty in Infrastructure Projects?

Master's thesis in the Master's Programme Design and Construction Project Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The infrastructure industry is known for underestimating project risks. Monte Carlo simulation is a probabilistic risk analysis method that can quantify consequences of risks but is not frequently used in the infrastructure industry even though the method has been available for decades. The aim of this thesis was to investigate to what extent Monte Carlo simulations are used and how these simulations can be implemented into the risk management process in the Swedish infrastructure industry. The thesis is based on a literature study and an interview study with five consultants and three experts from the Swedish Transport Administration.

The main findings are that Monte Carlo simulations seldom are used in the Swedish infrastructure industry today and that there is a difference between consultants and clients in perception of the benefits of Monte Carlo simulations. Consultants mostly appreciate the Monte Carlo method while the government client experts do not believe the benefits outweigh the added costs. Furthermore, the study indicates that Monte Carlo simulations can improve the risk management process by clearly visualizing and communicating risks to project participants, and that it should be possible to implement Monte Carlo simulations in many projects even without extensive knowledge of the method.

Key words: risk, risk management, risk analysis, Monte Carlo simulation, Monte Carlo method

Riskhantering i infrastrukturbranschen
Hur kan Monte Carlo-simuleringar reducera osäkerhet inom infrastrukturprojekt?

Examensarbete inom masterprogrammet Organisering och ledning i bygg- och fastighetssektorn

VETLE RUUD BRÅTEN
Institutionen för Teknikens ekonomi och organisation
Avdelningen för Service Management and Logistics
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SAMMANFATTNING

Infrastrukturbranschen är känd för att underskatta projektrisker. Monte Carlo-simuleringar är en probabilistisk riskanalysmetod som kan kvantifiera risker, men metoden används sällan inom infrastrukturbranschen även om den varit tillgänglig i årtionden. Syftet med detta arbete är att undersöka om och hur Monte Carlo-simuleringar används i infrastrukturbranschen i Sverige. Arbetet är baserad en litteraturstudie och en intervjustudie med fem riskkonsulter och tre riskspecialister från Trafikverket.

Av studien framkom det att Monte Carlo-simuleringar sällan används inom den svenska infrastrukturbranschen i dagsläget och att det eksisterar en skillnad i hur riskkonsulter och deras kunder uppfattar värdet av Monte Carlo-simuleringar. Riskkonsulter är generellt positiva till Monte Carlo-simuleringar, medan deras kunder inte uppfattar att värdet som dessa simuleringar skapar överstiger kostnaderna. Vidare har studien visat att Monte Carlo-simuleringar kan förbättra riskhanteringsprocessen genom att tydligt visualisera och kommunicera risker till alla deltagare i ett projekt, och att Monte Carlo-simuleringar kan implementeras i de flesta projekt även utan omfattande kunskaper om metoden.

Nyckelord: risk, riskhantering, riskanalys, Monte Carlo-simulering, Monte Carlo-metoden

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Preface

This thesis marks the end of my master's degree in Civil engineering at Chalmers University of Technology. Five years of studies which have given me new knowledge and great experiences now come to an end.

I would like to thank my supervisor at Chalmers University of Technology, Jan Bröchner, for all his help and feedback on the thesis, as well as all the participants of the interview study for sharing their knowledge of risk management. Lastly, I would like to thank Kristoffer Sideby for his support at Norconsult.

Gothenburg, January 2019

Vetle Ruud Bråten

1 Introduction

This first chapter is a short introduction to the area of risk management and why this is an interesting area to study. It begins with a short background to the topic, before the problem formulation is presented, and ends with a brief outline of the rest of the report.

1.1 Background

"If you don't risk anything, you risk even more." – Erica Jong

Bissonette (2016) explains how the implementation of risk management concepts can be one of the main factors deciding if a project is successful or unsuccessful in achieving project objectives. The importance of risk management is also acknowledged by the Project Management Institute which has defined risk management as one out of ten knowledge areas within project management (Project Management Institute, 2017). The purpose of project risk management is to increase the likelihood of favorable events or opportunities and reduce the likelihood of adverse events or threats, and despite its importance to project success, risk management is rarely managed with the same caution as other project management processes (KarimiAzari *et al.*, 2011). The risk management process can be divided into several parts, which according to Bissonette (2016) can be aggregated into the following four steps: (1) project planning, (2) identification and analysis of risks, (3) determination and implementation of risk responses, and (4) monitor and control risks and risk responses.

This thesis focuses on one part of step number three, regarding quantification and analysis of the risks. The purpose of risk analysis is to help decision makers make better decisions although the future is uncertain (Vose, 2008). Flyvbjerg, Holm and Buhl (2002) conclude in their study that costs are underestimated in 9 out of 10 transportation infrastructure projects, with an average of 28% higher cost than estimated over all transportation project types. In Sweden, Lundman (2011) found that most road and railway projects are characterized by major cost overruns compared to the first estimates, and that the estimates on average increased with 100% from the first to the last estimate. One method frequently used to address this uncertainty is adding an extra contingency sum to the project estimate, but according to Taroun (2014), better risk management methods are available.

Monte Carlo simulations are a probabilistic risk analysis method which can be used to quantify consequences of risks (Munier, 2014). Monte Carlo simulations and other probabilistic methods have been available to risk managers for decades, but are not frequently used in the infrastructure industry today (Senesi, Javernick-Will and Molenaar, 2015). Further, Senesi, Javernick-Will and Molenaar found both barriers and benefits from implementing probabilistic risk analysis, where some benefits were the ability to manage project schedules, project costs and project risks in a better way. This suggests that Monte Carlo simulations and how they can reduce uncertainty in infrastructure projects can be an interesting area to examine.

1.2 Problem formulation

This thesis aims to examine how Monte Carlo simulations can improve the predictability of project outcomes of infrastructure projects in Sweden, and this will be analyzed with the support of the following research questions:

- How are risk analyses conducted in the industry today and how can this process be improved?
- How can Monte Carlo simulations be implemented as a part of the risk management process to reduce uncertainty and improve predictability in infrastructure projects?
- How can infrastructure consultants use Monte Carlo simulations to help their customers better understand risk and uncertainty in infrastructure projects in the future?

1.3 Outline

This thesis is divided into five chapters which address different parts of the topic quantitative risk management within the infrastructure industry. Chapter one is a short introduction to the topic, presents the scope of the thesis, and in this section, presents the outline of the report. Chapter two describes the research methodology used and chapter three presents and summarizes relevant theory in a literature review. Chapter four presents the results of the interview study before the discussion are presented in chapter five. Chapter six answers the research questions and concludes the report.

2 Methods

This research study has been conducted as a qualitative study in two parts. The first part, presented in Chapter 3, is a literature review of relevant theory within the area of project risk management and Monte Carlo simulations. The second part consists of a qualitative interview study, where the empirical data that form the basis for the analysis are gathered. This part is presented in Chapter 4.

2.1 Literature review

The basis for the theory, presented in Chapter 3, was collected by searching for literature within the area of risk management and Monte Carlo simulations. The literature used consists of peer-reviewed scientific journal articles, conference proceedings, standards developed by relevant organizations and books. Searches were conducted in the electronic databases Science Direct, Scopus, ProQuest and Summon with keywords such as: "risk", "risk management", "Monte Carlo simulations", "uncertainty management", "project risk", "infrastructure risk". Searches were also done directly in five relevant journals: International Journal of Project Management (IJPM), Project Management Journal (PMJ), Journal of Construction Engineering and Management (JCEM), IEEE Transactions on Software Engineering (TSE) and International Journal of Risk and Contingency Management (IJRCM). The references used are published within the period from 1992 to 2018 with the majority of the literature being published in 2006 or later.

2.2 Semi-structured interviews

The empirical data was gathered through in-depth semi-structured qualitative interviews with eight experienced risk managers from the infrastructure industry. The nature of semi-structured interviews, with a list of topics to be discussed and the possibility for follow-up questions made it possible to gather the participants' knowledge and perceptions of the area of risk management within the infrastructure industry (Mason, 2002). Four of the interviews were carried out face to face in a quiet meeting room, three interviews with Skype audio and one interview were conducted via Skype with video enabled. All eight interviews were conducted by the same interviewer, the author of this thesis, within the time frame June to September 2018. Face to face interviews and partly Skype video interviews allow the interviewer to observe body language and by having the same interviewer for all interviews, the interviews should be more uniform even if they were conducted at different dates and locations (Bryman and Bell, 2007). The audio of all interviews was recorded on a smartphone, or by a Skype add-in to enable replays of the interviews if any uncertainties would arise.

2.2.1 Participants

The eight participants of the interview study were selected based on their experience of risk management in infrastructure projects, and all were recommended as participants by someone within their organization or professional network. It was difficult to find the right participants to the study. Many risk managers redirected the request to participate when the term Monte Carlo simulation was mentioned.

Five out of the eight interviewees have a master's degree within risk management from Lund University, and all of the participants are working with risk management on a daily basis. Three of the participants work as safety/risk specialist or strategic planner within the Swedish Transport Administration, while the five others are risk consultants employed by three different consultancy organizations ranging from 1 to 5000 employees. All participants have four or more years of experience of risk management, and six of the interviewees have ten or more years of experience. Table 1 summarizes the respondents, their organizations, the number of employees within the organizations, positions, age, and experience of risk management. The participants' experience of risk management made them familiar with specific terms and expressions within the area of study. Some small uncertainties that arose during the interviews were resolved directly with some extra explanation by the interviewer.

Table 1 - Summary of respondents, their organizations, number of employees within the organizations, positions, age, and experience of risk management. In the table, STA is short for the Swedish Transport Administration.

Interviewee	Organization	Employees	Position	Age	Experience
A	STA	7000	Safety specialist	36 - 50 years	10 + years
B	STA	7000	Risk specialist	36 - 50 years	10 + years
C	STA	7000	Strategic planner	20 - 35 years	4 - 9 years
D	Consultant	500	Risk consultant	36 - 50 years	10 + years
E	Consultant	1	Management/risk consultant	50 + years	10 + years
F	Consultant	5000	Risk consultant	36 - 50 years	10 + years
G	Consultant	500	Risk consultant	20 - 35 years	4 - 9 years
H	Consultant	5000	Risk consultant	36 - 50 years	10 + years

2.2.2 Interview questions

The interview questions were developed based on the literature review to gather information on the risk management practice in infrastructure projects carried out by the Swedish Transport Administration or consultants working for the Swedish Transport Administration. The questions were a combination of open and closed questions and were divided into five parts: (A) Context, (B) Risk management, (C) Monte Carlo simulations, (D) Future of risk management, and (E) Closure, see the Appendix for the complete interview guide. The questions about context were mostly closed questions, and some of these were also pre-categorized to make it easier to summarize the answers in the results. The rest of the questions were open questions to allow for discussions about how the participants perform risk management in their projects.

The interview questions were pre-tested on two people with knowledge of the area of study to see if the questions were easy to understand, and for the interviewer to practice before the interviews. Some ambiguities were discovered and resolved before the interviews. The interview guide was sent out to all participants in advance so that the participants could prepare thoughts on the topics beforehand. This was done to make the interviews more efficient but could also lead to pre-determined answers from the participants. The interview guide was written in Swedish, and all the interviews were conducted in Swedish.

2.3 Ethical considerations

The interview study was conducted in an ethical manner where all participants have given their consent of participation. Before the interviews started, a short introduction was given to inform the participants that all answers were anonymized, and the participants were asked if it was ok to record the interviews. The questions were asked openly to reduce any leading questions or biased answers (Mason, 2002). Any examples of the participants' risk management work showed during or after the interviews were given confidentiality and were only used for the author's understanding of the risk management process used by the participants and are not shared in the report.

2.4 Limitations

The report focuses on risk management in the infrastructure industry. All participants are working in Sweden, so the results cannot be generalized to other geographical areas because of cultural differences. A total of eight interviews were conducted, and this number should preferably be higher. All participants are either employed at the Swedish Transport Administration or have participated in several risk management projects for the Swedish Transport Administration, which further reduces the generalizability of the results.

Another limitation of this study is that no case study has been carried out. The literature within the area of interest are compared to results for the interview study, but preferably one or several case studies should have been included to see if the theoretical benefits of probabilistic risk analysis apply to the infrastructure industry.

3 Literature review

This chapter gives an introduction to risk and risk management with the focus on quantitative risk assessment and how Monte Carlo simulations can reduce uncertainty and improve predictability in projects.

3.1 Risk

There is no universal definition of risk in the area of risk management, and the risk assessment field struggles to find a shared terminology for risk (Aven, 2017). Raftery (1994) describes risk and uncertainty together as when it is expected that the actual outcome will deviate from the forecasted value:

> *Risk and uncertainty characterize situations where actual outcome for a particular event or activity is likely to deviate from the estimate or forecasted value* (Raftery, 1994, p. 5).

This definition does not differentiate between risk and uncertainty, such as the three other definitions presented here do. More on the difference between risk and uncertainty is presented in Section 3.1.1. The International Organization for Standardization (2018) defines risk as an effect of uncertainty on project objectives:

> *effect of uncertainty on objectives* (ISO 31000, p. 1).

The Project Management Institute (2017) recognizes that risks can have both positive and negative outcomes:

> *An uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives* (Project Management Institute, 2017, p. 720)

Smith, Merna and Jobling (2013) define risk as when the outcomes of a decision can be attached to known probabilities, inspired by Frank Knight's definition of risk and uncertainty (Knight, 1921):

> *risk exists when a decision is expressed in terms of a range of possible outcomes and when known probabilities can be attached to the outcomes* (Smith, Merna and Jobling, 2013, p. 4)

Based on these four definitions, it can be argued that risk has something to do with the uncertainty of outcomes. In the two following sections, two other central aspects of risk are discussed, namely if risk can be positive as well as negative, and the difference between risk and uncertainty.

3.1.1 Uncertainty versus risk

As presented above, Smith, Merna and Jobling (2013) define risk as when the possible outcomes of a decision can be attached to known probabilities. In contrast to this, they define uncertainty as something when there is more than one possible outcome, but you cannot know the probabilities of the different outcomes:

> *uncertainty exists when there is more than one possible outcome of a course of action but the probability of each outcome is not known (frequently termed estimating uncertainty)* (Smith, Merna and Jobling, 2013, p. 4)

Both Project Management Institute's (2017) and ISO 31000's definitions of risk use the term uncertainty without defining what uncertainty is. Hirshleifer and Riley (1992) disregard the difference between risk and uncertainty because it has no practical purposes. In the same way as Smith, Merna and Jobling, Raftery (1994) distinguishes between risk and uncertainty in the way that risk has quantifiable attributes, whereas uncertainty does not, and therefore risks are insurable, but uncertainties are not. Furthermore, Raftery argues that even if the differentiation between risk and uncertainty has some conceptual value, the practical usefulness is doubtful as most business decisions are made without statistical data and calculations.

As Raftery (1994) argues that the difference between risk and uncertainty does not have any practical use, so for this report the terms will be used interchangeably.

3.2 Risk management process

According to Munier (2014), it is widely accepted by risk specialists that risk management involves the following nine phases:

(1) Data and Initial Conditions
(2) Planning
(3) Risk Identification
(4) Risk Assessment and Analysis
(5) Execution and Remediation
(6) Sensitivity Analysis
(7) Updating, Monitoring and Control
(8) Closing
(9) Reporting

These phases start in this natural sequence but do not strictly precede each other (Munier, 2014). The whole risk management process is an iterative process that often requires continuous feedback during the whole project life cycle.

3.3 Risk management standards

There exist multiple guides, standards or methods to share knowledge and experience about risk management. Two of the leading standards in the field are the Project Management Body of Knowledge (PMBOK) and ISO 31000 (Senesi, Javernick-Will and Molenaar, 2015; Crnković and Vukomanović, 2016). These will be explained more in detail in the following sections.

3.3.1 PMBOK

Project Management Institute has created a guide which covers all areas of project management and has categorized ten knowledge areas, where project risk management is recognized as one of those (Project Management Institute, 2017). The project risk management process presented by the Project Management Institute is divided into seven parts which aim at increasing the likelihood of positive risks and reduce the likelihood of negative risks. These seven parts are: (1) Plan Risk Management, (2) Identify Risks, (3) Perform Qualitative Risk Analysis, (4) Perform Quantitative Risk Analysis, (5) Plan Risk Responses, (6) Implement Risk Responses, and (7) Monitor Risks. These are described below:

(1) Plan risk management
The first step is about deciding how to implement risk management for the specific project and creates a risk management plan that describes the risk strategy, methodology, roles and responsibilities, funding, timing, risk categories, stakeholder risk appetite, definitions of risk probability and impacts, probability and impact matrix, reporting formats and how to track the risks. This step is often carried out with the help of expert judgment and experience from similar projects, which is gathered as a part of a project kick-off meeting.

(2) Identify risks
To identify project risks, the Project Management Institute recommends arranging risk workshops and use brainstorming. The goal is to get a complete list of project risks. Everyone is encouraged to help identify all possible risks, and this can be done either in free-form sessions or by using more structured techniques. Risk categories and checklists can be useful tools together with interviews of experienced project participants and stakeholders. When the identify risks step is finished, all risks should be organized in a risk register for further analysis.

(3) Perform qualitative risk analysis
Qualitative risk analysis is the development of a prioritized project risk register, where the most critical risks are identified. Project Management Institute mentions three ways to analyze the risk at this point in the risk management process. The first is to assess the quality of the risk data, the second to do a risk probability and impact assessment with tools such as probability and impact matrices (which are explained more in detail in Section 3.4.1), and the third, to assess other risk parameters such as urgency, manageability, and controllability.

(4) Perform quantitative risk analysis
To perform quantitative risk analysis is not necessary for all projects, but it is appropriate for large and complex projects or projects where a key stakeholder requires it. Simulations like Monte Carlo simulations are typically used, and these are presented in detail in Section 3.4.2. Monte Carlo simulations together with sensitivity analysis, decision tree analysis, and influence diagrams are useful tools in this step.

(5) Plan risk responses
This step is the process of evaluating options, strategies, and actions for both individual and overall project risks. The goal is to minimize the impact of the risks identified and analyzed in the earlier steps.

(6) Implement risk responses
To implement risk responses is the process of actually implementing the agreed upon risk responses in step (5)

(7) Monitor risks
This last step in the overall risk management process developed by the Project Management Institute is to monitor the development of the risks' outcomes, identifying new risks, and continuously monitor the development of all risk. Some might become obsolete, while other risks might become more critical

during a project's lifecycle, and it is therefore vital to monitor these developments all the way until the project is finished.

3.3.2 ISO 31000

ISO 31000:2018 Risk Management is a document created to help organizations to manage risks, making decisions, setting and achieving objectives and improving performance. The International Organization for Standardization (ISO) has developed standards within several other areas as well, with ISO 9001 for Quality Management as one of the most famous.

ISO 31000 explains how an organization can develop their principles, framework, and process for risk management. These mechanisms, which are summarized in
Figure 1, can already exist or partly exist within the organization and might need to be adapted to manage risks in an efficient, effective and consistent way. One of the main changes in the newest version, ISO 31000:2018, compared to the previous one, is that there is greater emphasis on risk management as an iterative process and the fact that new knowledge can lead to a need for revising the risk management process.

In this chapter, the process described in ISO 31000 is presented. The process, which is illustrated in
Figure 2, consists of eight parts: (1) Communication and Consultation, (2) Scope, Context and Criteria, (3) Risk Identification, (4) Risk Analysis, (5) Risk Evaluation, (6) Risk Treatment, (7) Monitoring and Review, and (8) Recording and Reporting. Note the arrows around the process map, which indicate that the process should be seen as an iterative process and underline the importance of continual risk management during the whole project life cycle.

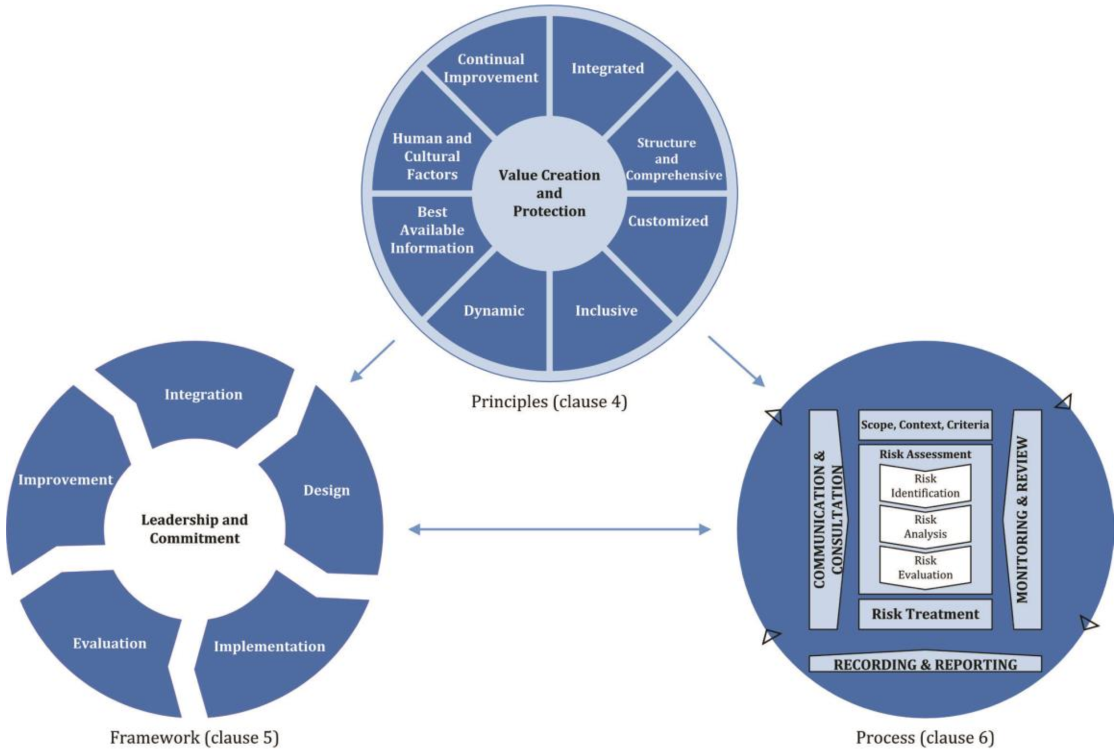

Figure 1 – An overview of the principles, framework, and process described in ISO 31000.

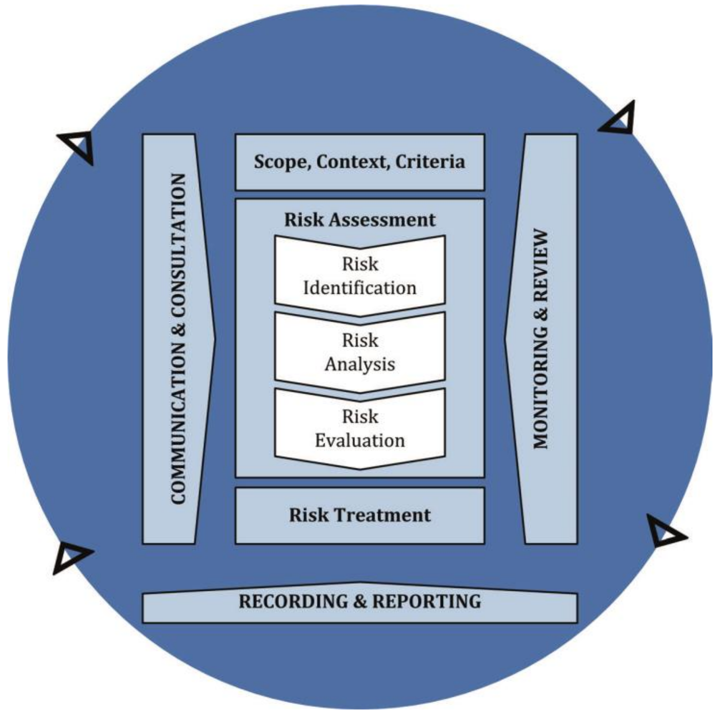

Figure 2 – The risk management process presented in ISO 31000

(1) Communication and Consultation

This first step of the risk management process presented in ISO 31000 has the purpose of helping relevant stakeholders to understand the risks and the assumptions which are made, in order to use the risk analysis as a basis for decision making. By bringing different areas of expertise together, this step ensures that different views on the risk management process are included and that the result of the process enables decision-makers to make the best decisions available.

(2) Scope, Context, and Criteria

The standard states that the purpose of defining the scope, context, and criteria is to modify the risk management process to enable effective risk assessment and risk treatment. Defining the scope is about planning which approaches to choose and can include defining which objectives to consider and which decisions to make, expected outcomes, appropriate risk management tools, required resources and connections with other projects, processes, and activities. Defining the context covers both the internal and external context, namely the environment for which the risk management will be conducted. Defining the criteria for risk management is the process of deciding what amount of risk the organization is considering as acceptable and not, defining how to measure the magnitude of the relevant risks and how these risks might affect each other.

Risk Assessment

The next step in the process described in ISO 31000 is the Risk Assessment, which in turn are divided into three parts: risk identification, risk analysis, and risk evaluation. The standard explains that the Risk Assessment should be managed systematically, iteratively and collaboratively. The best available information based on the knowledge of stakeholders should be used.

(3) Risk Identification

Risk identification is conducted to ensure that all relevant risks are considered. The purpose of this step is to find and describe all relevant risks, both positive and negative.

(4) Risk Analysis

The International Organization for Standardization describes the risk analysis as the process of understanding the characteristics of the risks and determining the level of each risk. The risk analysis can be conducted with a varying degree of detail and can be both qualitative, quantitative, or a combination of these. The risk analysis should consider the likelihood and consequences, complexity and sensitivity of risks. The analysis is often based on several assumptions that might limit the usefulness of the analysis. All assumptions, limitations, and techniques used in the analysis should be documented and communicated to decision makers to enable the best possible decisions to be made.

(5) Risk Evaluation

Risk evaluation is described as the process of comparing the results of the risk analysis with the criteria defined in (2). The standard explains that this comparison determines what actions are required. The actions can range from no action at all if the risk level is acceptable, to consider risk treatment options, conduct further analysis, and reconsider objectives.

(6) Risk Treatment
Risk treatment is the process of selecting and implementing alternatives for managing the risks. When the risk criteria are compared to the risk analysis, this step makes sure that the best possible risk treatment option is selected and decides who is responsible for the chosen actions.

(7) Monitoring and Review
The purpose of monitoring and reviewing is to ensure that the risk management process is conducted effectively, and this should take place in all stages of the process. Ongoing monitoring and periodic review should improve the quality and effectiveness of the risk management process within the organization.

(8) Recording and Reporting
To provide information, improve risk management activities, and keep new knowledge within the organization, recording and reporting is an essential part of the risk management process. The process and its outcomes should be reported to improve the interaction between stakeholders and support the organization's decision making.

3.3.3 Summary of risk management standards

The risk management process presented by Bissonette (2016), Munier (2014), Project Management Institute (2017), and ISO 31000 are all similar in nature and consist mostly of the same steps, even though some of the steps are denoted differently, and some steps in one method are divided into several steps in another. See Figure 3 for a graphical summary of the four methods and how they differ. As can be seen, the nine-step method of Munier includes three steps which are not included by Bissonette, PMBOK and ISO 31000, namely (1) data and initial conditions, (2) sensitivity analysis, and (3) closing. Otherwise, the four methods are very similar in structure.

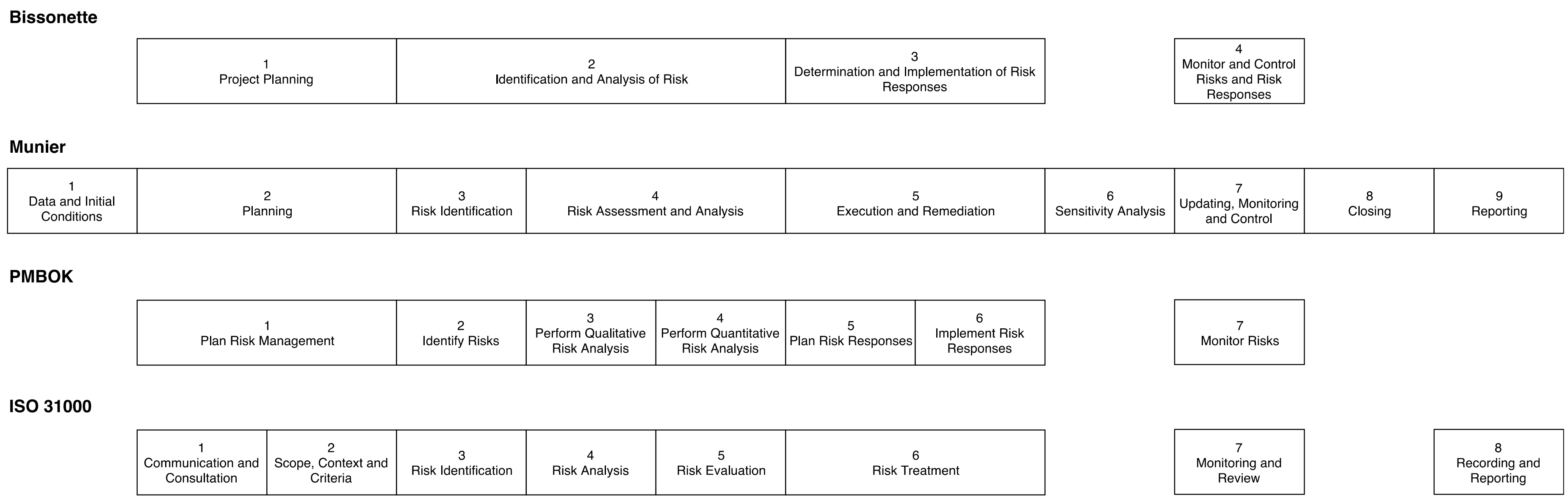

Figure 3 – A graphical summary of the risk management methods presented by Bissonette, Munier, PMBOK and ISO 31000.

3.4 Risk analysis

According to Bissonette (2016), formal risk management can be divided into two parts of risk analysis. These two parts are qualitative risk analysis where the individual risks are assessed and quantitative risk analysis where the total impact on the project is analyzed.

3.4.1 Qualitative risk analysis

The purpose of qualitative risk analysis is to assess the importance of all project risks relative to each other in order to prioritize which risk to focus on in the risk response phase (Bissonette, 2016). Bissonette discusses some useful tools frequently used by risk managers such as risk registers and risk matrices.

A simple risk register includes all risks, their risk categories, their subjective risk assessment and possible risk responses (Bissonette, 2016). The risk register is often created already in the risk identification phase. Risk matrices are one of the most popular tools within qualitative risk analysis (Dziadosz and Rejment, 2015; Bissonette, 2016). A risk matrix evaluates the relative risk levels by multiplying each risk's probability with its impact. A simple risk matrix with both probability and impact evaluated from 1 to 5 are shown in Figure 4, but the scales can be modified to conform with each project, for example, to put a higher emphasis on low probability, high impact risks.

Impact (or consequence)	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
		Probability (or likelihood)				

Figure 4 – A risk matrix with impact and probability on a scale from 1 to 5. The risks with a score of 10 or higher are categorized as high risks, the ones with a score between 5 and 9 as medium risks and the ones with scores below 5 as low risks. (Figure adapted from Bissonette, 2016)

3.4.2 Quantitative risk analysis with Monte Carlo simulations

Khedr (2006) describes quantitative risk analysis as the process where the risk manager quantifies the total risk imposed on the project. Senesi, Javernick-Will and Molenaar (2015) note that a probabilistic approach will not eliminate the risks, but should provide a better basis for managers to make the right decisions. Further, Senesi, Javernick-Will and Molenaar (2015) explain that in probabilistic risk analysis, the uncertainty of the variables is described by probability distributions, and techniques such as simulation and decision tree analysis are used to quantify the risk level of projects.

Monte Carlo simulations, or the Monte Carlo technique, is a probabilistic risk quantification method that has become one of the most popular in the area of risk quantification (Smith, Merna and Jobling, 2013). O'Connor and Kleyner (2012) explain that Monte Carlo simulations are a class of probabilistic computational algorithms that use repeated sampling of random variables to determine all possible scenarios and the probabilities of these. The method was developed in the 1940s by three scientists working on the Manhattan Project and has applications in several areas, such as business, engineering, science, and finance (Thomopoulos, 2013).

According to Kwak and Ingall (2007), the main advantage of using Monte Carlo simulation is that it is a powerful tool to help the project participants understand and quantify the potential effects of risk on a project. Instead of a single-point estimate, Monte Carlo simulations use a range of possible outcomes when it takes probability distributions as input and runs the simulation hundreds or thousands of times. By doing this, a Monte Carlo simulation includes all possible scenarios that might occur in an uncertain situation (Khedr, 2006). Robert and Casella (2004) explain that Monte Carlo simulations are based on the law of large numbers and according to Munier (2014), the many iterations conducted in a Monte Carlo simulation makes the output more accurate than other methods that only consider one of the possible scenarios.

Lorance and Robert (2001, p. 25) identify the steps of a Monte Carlo simulation as the following: (1) define the capital resources by developing the deterministic model of the estimate, (2) identify the uncertainty in the estimate by specifying the possible values of the variables in the estimate with probability ranges (probability distributions), (3) analyze the estimate with simulation, and (4) make a decision based upon the results of the Monte Carlo analysis. The Monte Carlo process is summarized in Figure 5 where the input variables are expressed as probability distributions, and the output from the simulation model is visualizations of the results and statistical data for further analysis.

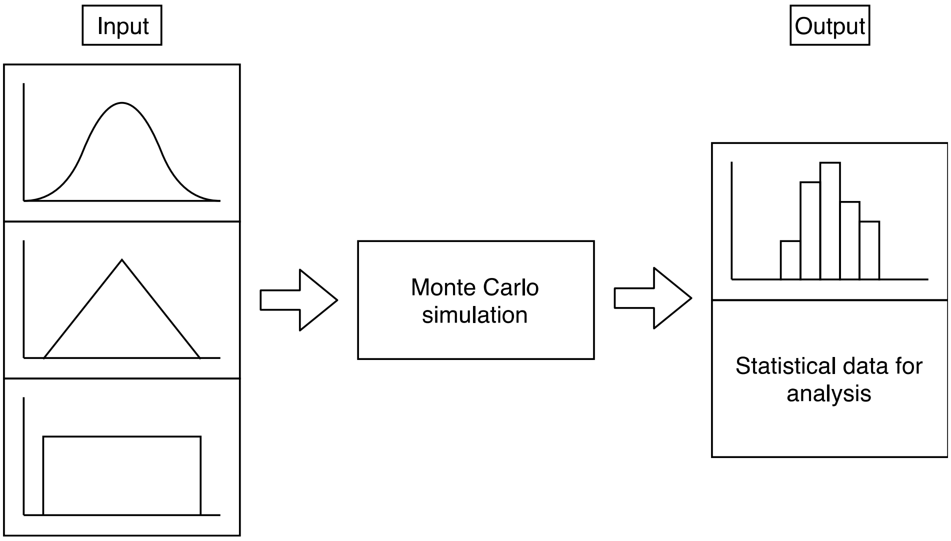

Figure 5 – An overview of the Monte Carlo simulation process. The input variables are represented by frequently used probability distributions (normal, triangular and uniform distribution), and the output of the Monte Carlo simulation is illustrated by graphs and statistical data for analysis (Figure adapted from El-Reedy, 2016)

The input to a Monte Carlo simulation consists of random variables and probability distributions that describe the uncertainty of these variables. According to Smith, Merna and Jobling (2013), there are four probability distributions commonly used within risk analysis: (1) normal distribution, (2) beta distribution, (3) rectangular distribution and (4) triangular distribution. There are several other probability distributions which can be useful in some cases, but these four is often enough to approximate most random variables within risk analysis. Below are the four probability distributions, mentioned by Smith, Merna and Jobling, and their characteristics.

(1) Normal distribution
The normal distribution is a bell-shaped probability distribution and is the most widely used distribution within many areas (Thomopoulos, 2013). The shape of a normal distribution is illustrated in Figure 5, the upper probability distribution among the inputs.

(2) Beta distribution
The beta distribution can take on many different shapes depending on the two parameters (k_1, k_2) where $k_1 > 0$ and $k_2 > 0$. The random variable is limited by a and b where $(a \geq x \geq b)$.

(3) Rectangular distribution (uniform distribution)
The rectangular distribution is also known as the uniform distribution and looks like the lower probability distribution in Figure 5 (O'Connor and Kleyner, 2012). The variable x has a constant probability on the interval (a, b) (Thomopoulos, 2013).

(4) Triangular distribution
The triangular distribution is often applied in engineering approximations because of its ease of use. The distribution looks like the middle probability

distribution in Figure 5 (note that the high point can be skewed to the left or right), and is also referred to as three-point estimator with the lowest, most likely and highest approximation being the three points (a, c, b), where (a, b) defines the limits of the distribution, and (c) the point with the highest probability (O'Connor and Kleyner, 2012).

O'Connor and Kleyner (2012) explain that the choice of probability distributions for the random variables need to represent the current state of knowledge. According to Smith, Merna and Jobling (2013), it is essential to transfer the knowledge from the risk identification phase to the risk assessment to reflect the real risk affecting the project. Further, Smith, Merna and Jobling claim that often the spread in the chosen probability distributions is too conservative, which can result in an underestimation of the actual risk of the project, and that it is of importance to discuss the assumptions which are the basis of the risk analysis to avoid anchored estimates.

The original Monte Carlo method as presented in this report does assume independent random variables even though this seldom reflects reality. O'Connor and Kleyner (2012) note that correlated variables should be identified and simulated as such in order to avoid biased results. Chau (1995) concluded that the independence assumption resulted in an underestimation of the real variance. Peleskei et al. (2015) claim that more than half of the cost elements in a construction project are correlated to a substantial level, and that correlation matrices should be included in the Monte Carlo simulations to reflect reality to a greater extent. There are several different methods to create correlation matrices to be used for Monte Carlo simulations, and one of the most frequently used is the Spearman rank correlation (Chou, 2001; Peleskei et al., 2015). The Spearman correlation method ranks the correlation coefficients for all pairs of risk elements between -1 and +1, where -1 means a perfectly negative correlation, 0 no correlation, and +1 a perfect positive correlation (Peleskei et al., (2015). The matrix created can then be used as input to the Monte Carlo simulations together with the random variables described by probability distributions described above.

Nevertheless, Senesi, Jarvernick-Will and Molenaar (2015) found clear benefits from using probabilistic risk analysis such as Monte Carlo simulations, as well as barriers that need to be overcome to implement probabilistic analysis successfully. The benefits mentioned by Senesi, Jarvernick-Will and Molenaar included better management of project schedule and costs, increased confidence when making decisions, the ability to express risks clearly, better risk management, and better internal communications. The barriers mentioned were lack of support from the organization, lack of policies and procedures, difficulties understanding the results and the lack of knowledge.

Loizou and French (2012) stress that the Monte Carlo simulation model should be used cautiously with an emphasis on the quality of the input being used, as the quality of the output is a direct consequence of the quality of the input, and that the results should be used in combination with a consideration of human judgment and decision making. Kwak and Ingall (2007) assert that Monte Carlo simulations can quantify the uncertainty in project schedules and budgets statistically and therefore help the manager better understand the effects of different variables. Another essential advantage according to O'Connor and Kleyner (2012) is the ease of comprehension of sensitivity analysis and what-if scenarios that Monte Carlo simulations enable.

As shown above, Monte Carlo simulations can lead to better management of project elements such as schedule and costs, as well as help project participants get a deeper understanding of the project at hand and which uncertainties that exist. Monte Carlo simulations should be implemented into the risk management process as a natural extension after the qualitative risk assessment. The most important part of a Monte Carlo simulation is to decide how to describe the random variables and correlations between these. This is preferably done with the support of historical data but can also be approximated with the help of expert experience if historical data does not exist or is not applicable to the project. The results of the Monte Carlo simulations should be used to illustrate the risks and uncertainties of the project to all project participants and will hopefully lead to a better risk management process and help the management towards better management decisions. The overview of the Monte Carlo method in Figure 5, can be extended to the complete process shown in Figure 6.

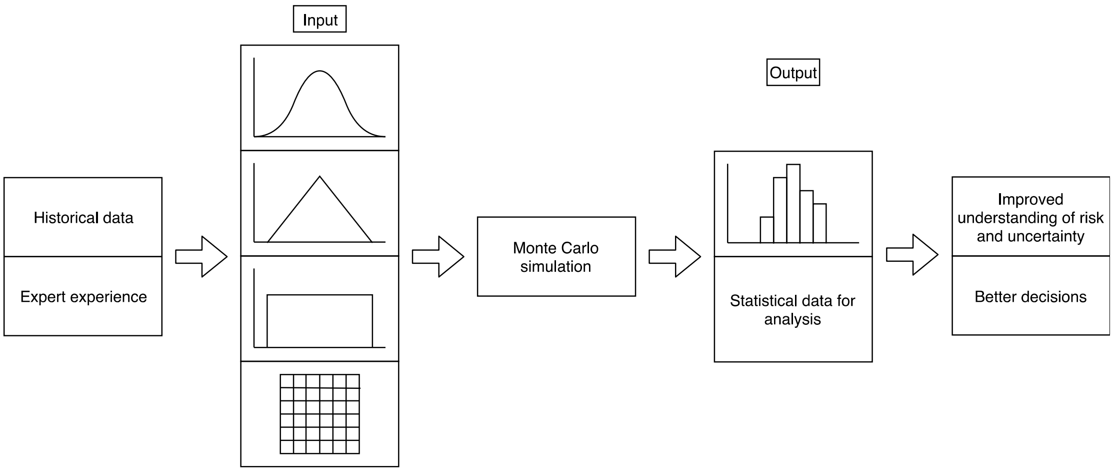

Figure 6 – The complete Monte Carlo process which considers how to gather and formulate the input (random variables formulated as probability distributions and the correlation matrix) and what to expect as a consequence of the output.

4 Results

This chapter presents the results from the interview study. Eight interviews were conducted, and the background of the eight interviewees can be found in Section 2.2. The complete interview guide is attached in the appendix.

4.1 Risk and risk management

All eight participants were asked to define risk and risk management within infrastructure projects from their point of view. The definitions differed a lot, but five of the interviewees mentioned that risk is uncertainties that might affect the project goals.

Five of the participants divided risk into two categories. They differentiated between disaster risks such as technical risk, natural disaster risk or sabotage and project risks such as time, costs and quality. Interviewee E also included the working environment, goodwill/badwill, environmental risks and political risks as a part of project risks.

Out of the eight interviewees, six are using the ISO 31000 standard. The two other interviewees are using a method which is similar to or based on ISO 31000. All eight participants stressed the importance of adapting the method described in ISO 31000 to their area of expertise, as ISO 31000 is a general method which describes general risk management principles. Only three of the interviewees had heard about PMBOK and the method presented by the Project Management Institute. After some further discussions about PMBOK during the interviews, several of the participants described the method in PMBOK as very similar to the method in ISO 31000, and interviewee E pointed out that the structure of most risk management methods available today are quite similar.

4.2 Risk analysis

The most popular tool to analyze risks among the participants was risk matrices where the probability and impact of risks are multiplied to rank the risks and see which are most important to manage. All eight participants used risk matrices to some extent, and the most used matrix is where both probability and impact are ranked subjectively from 1 to 5. Two of the interviewees specifically noted that they sometimes use a different ranking system where the different rankings are given different weights in order to give higher importance to the impact than the probability in the matrix. Other methods of assessing risks which were pointed out by more than one participant were: risk lists, reports, and templates. For disaster risks, the worst-case scenario is often used because of their nature of low probability, high impact risks. It was pointed out by several interviewees that the low probability of disaster risks can lead to risks that are important to manage, such as the risk of train derail or fire in the electrical system, to be classified as low prioritized risks.

As support in the risk management process, four out of eight participants said they use statistics as input to their risk assessment methods. Two additional participants claimed to use statistics sometimes when it is available. The last two participants never use statistics in their methods. Most of the statistics available are for disaster risks, so statistics are seldom used for project risks according to the participants. When it comes to the use of experience, all eight interviewees explained that this is an essential input to their risk management process and that risk workshops are widely used as a tool to collect as much of the experience available in the project organization. Interviewee D stressed the importance of being aware of any biased reasoning during the collection of experience, but that it, unfortunately, is difficult to avoid altogether.

Three of the participants said that they take into account any correlation of risks when assessing the total risk within a project. Interviewee F argued that correlations are hard to assess and that they can be seen as domino effects. Three additional participants said they partially assess correlations between risks. Interviewee G stated that risk correlations are primarily applicable for project risks. The interviewees' responses regarding experience, statistics, and correlation when quantifying risks are summarized in Figure 7.

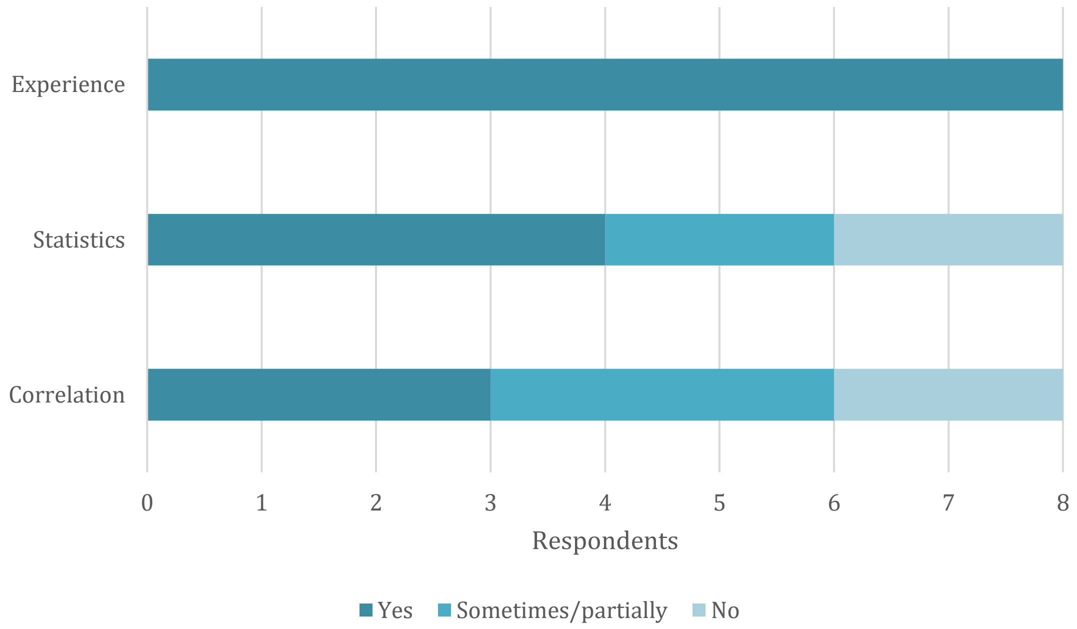

Figure 7 – Sources of input the respondents use and if the respondents consider the correlation between risks in their risk assessment process.

Six out of the eight participants use mostly Microsoft Excel when assessing risks, see Figure 8 for a summary of which software programs were used by the participants. Two of the interviewees who are employed at the Swedish Transport Administration did not use Microsoft Excel. One of these used Exonaut, a software customized for the Swedish Transport Administration, and the other one said that they always hire consultants to do the calculations and what software the consultants use are up to them to decide. In addition to Microsoft Excel, interviewee E used Oracle, Exonaut and R-Active RM, and stressed the importance of choosing software that is adapted to be used together. Both interviewee E and H named @Risk, an add-in to Microsoft Excel, which they use for Monte Carlo simulations.

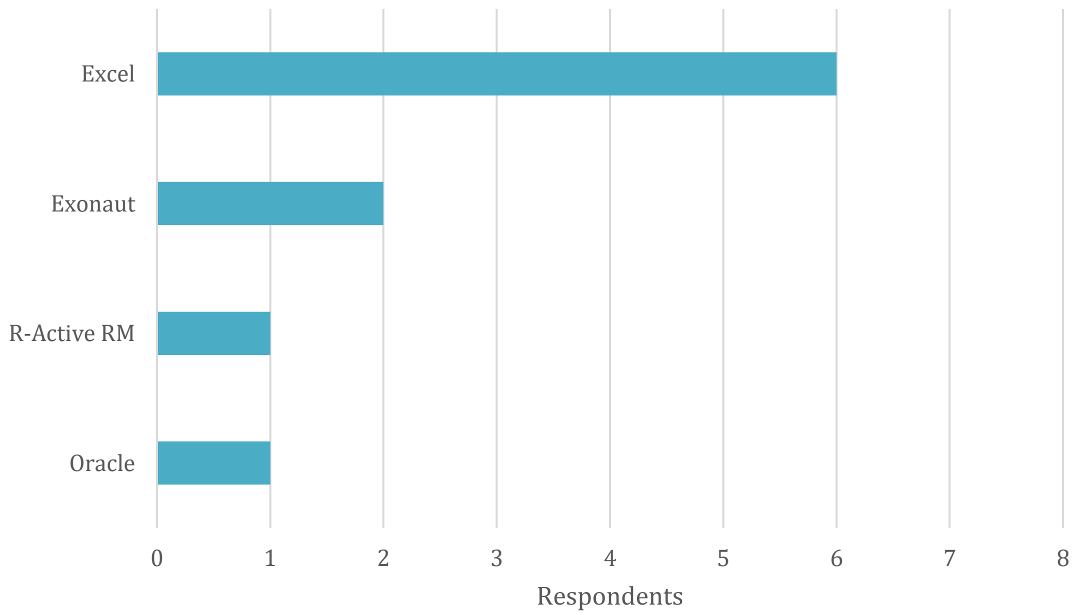

Figure 8 – Software used among the respondents. Some respondents use more than one software.

All eight interviewees stressed the importance of an iterative risk management process where the risk management process is revisited continually during the project.

4.3 Monte Carlo simulations

Seven out of the eight participants are familiar with Monte Carlo simulations to some degree, but only one of the respondents is using Monte Carlo simulations as a part of the risk management process, see Figure 9. Three more respondents have used Monte Carlo simulations once: Interviewee A said that the Swedish Transport Administration had tested Monte Carlo simulations as a part of a research project, but it is not something they have implemented into their risk management process. Interviewee D said he used Monte Carlo simulations very seldom but had made simulations as a part of his master's thesis where he quantified technical risks. Interviewee D told that he has discussed with some colleagues to implement Monte Carlo simulations into their risk management process in the future. Interviewee F had used Monte Carlo simulations once in a project and is considering using it more in future projects.

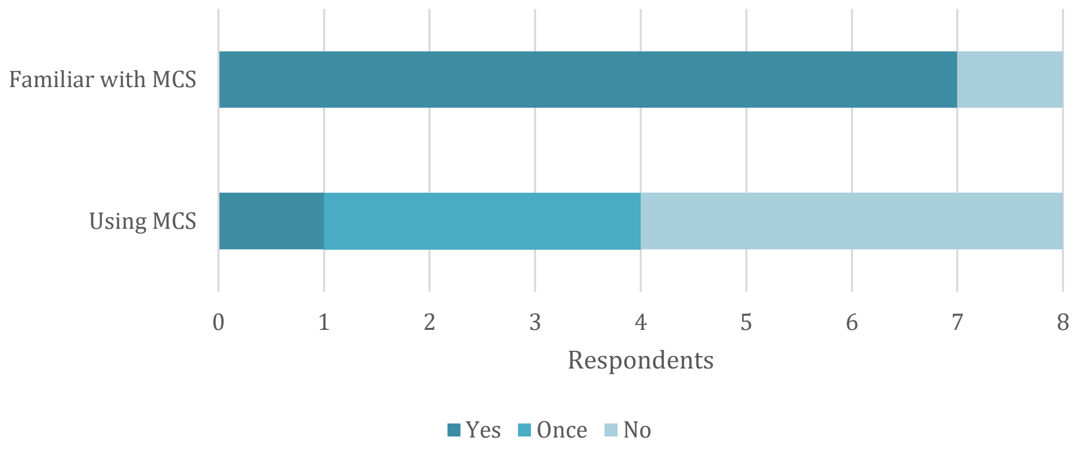

Figure 9 – Familiarity and usage of Monte Carlo simulations among the respondents.

The only of the participants that have used Monte Carlo simulations in more than one project have done so in other countries such as the Netherlands and Qatar. He explained that it has been challenging to convince customers in Sweden that Monte Carlo simulations create extra value. The results of the interview study show a trend where all five consultants believe that Monte Carlo simulations can create better risk estimations and therefore create value to the customer, but the customers are not willing to take the extra costs for the work needed to implement efficient Monte Carlo simulations into the project risk management process. This can be seen in the answers from the three participants working at the Swedish Transport Administration, where they do not believe that Monte Carlo simulations create extra value or better risk assessment in their projects. Both interviewee A and B believe there is too much uncertainty in the input to the simulations when the input is based on subjective data.

Some of the consultants also address the challenge of a statistical model based on subjective data, but all five consultants (interviewee D to H) believe that with the right process to gather and create the input to the Monte Carlo simulations, these simulations can create extra value to the customer. The consultant's biggest challenge is that their customers have no or little knowledge about Monte Carlo simulations, and therefore it is difficult to convince them that the extra costs of implementing Monte Carlo simulations can be beneficial for the project outcome. Another challenge that Interviewee D mentioned is that when the customer does not have any knowledge about Monte Carlo simulations, it is difficult to explain how to use the results of the simulations and that the customer often can see the results of simulations as definitive. Interviewee D stresses the importance of transparency of which input data that creates the basis of the simulations and how to read the results.

In contrast to all the consultants being positive to the implementation of Monte Carlo simulations, none of the three clients interviewed believe Monte Carlo simulations will improve their risk management process. One of the clients was not familiar with Monte Carlo simulations, while the two others did not believe that Monte Carlo simulations would result in better estimates of the risks facing a project. They explained their opinion by highlighting that the use of subjective input to a statistical model would not necessary result in better estimates than their risk matrices.

Out of the four participants that use or have used Monte Carlos simulations, three identify @Risk as their preferred software. Interviewee E, that uses Monte Carlo simulations the more frequently, names the combination of the software programs Oracle and Primavera for project risks, where the integration of both project scheduling, project cost, and Monte Carlo simulations are easy to handle and do not need much extra work.

4.4 Future of risk management

The feedback from the interview study regarding the future of risk management differed considerably, but all five consultants pointed out the implementation of Monte Carlo simulations as one interesting area of development. No one of the three risk managers at the Swedish Transport Administration mentioned Monte Carlo simulations. Other areas that were mentioned by more than one respondent were: understanding of Monte Carlo simulations, and risk management in general, transparency of the risk management process being used and communication between all players involved in the risk management process. Additionally, sensitivity analysis, software adapted for Monte Carlo simulations and standardized file formats were mentioned.

Out of the five pre-defined categories given to the interviewees (education, time, support from the management, economy, and prioritization of risk management), education, economy and prioritization of risk management were mentioned by five respondents, time by four respondents and support from the management by two respondents. The responses according to the pre-defined categories are presented in Figure 10.

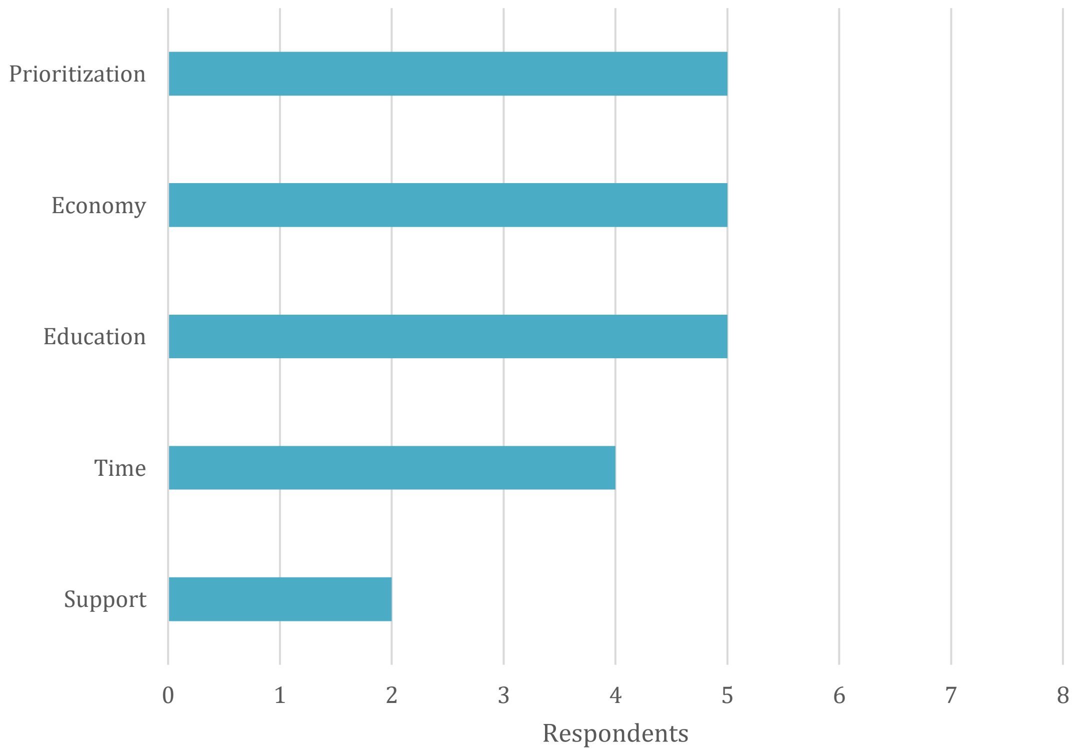

Figure 10 – What the respondents believe are most important to develop the risk management process. More than one answer per respondent is possible.

5 Discussion

This chapter will discuss the findings from the interview study and compare these to the relevant literature gathered in Chapter 3.

5.1 Risk management

In reviewing the literature, there were found various definitions of risk (Raftery, 1994; Smith, Merna and Jobling, 2013; Project Management Institute, 2017; ISO 31000). Similar results were found in this study where all eight respondents defined risk in their own words. Five out of eight defined that risk is uncertainties that might affect the project goals, which is similar to the definitions of the Project Management Institute and International Organization for Standardization.

Several different risk management processes, guidelines or standards are developed and are used in the industry today. In this report, four such are presented (Munier, 2014; Bissonette, 2016; Project Management Institute, 2017; ISO 31000). All these standards are very similar in their structure, and the current study found that ISO 31000 is the most used standard within the infrastructure industry today.

A possible explanation for this might be that the risk management process introduced in the PMBOK is a part of a complete project management process, where risk management is one out of ten different knowledge areas. PMBOK is probably more frequently used by project managers, in contrast to the risk specialists participating in this study. Another possible explanation might be that ISO is a well-known standardization organization with modern standards within several areas. Therefore, ISO standards are known to most people within the industry and clients might require their partners to use ISO 31000. It is interesting to see that all eight participants use some specified risk management process and that all participants point at the importance of adapting the standards to their projects, as well as to understand risk management as an iterative process. This is in accordance with the standards themselves (Project Management Institute, 2017; ISO 31000).

Risk matrices are undoubtedly the most frequently used risk assessment method according to the interviews. This result is consistent with those of Dziadosz and Rejment (2015) and Bissonette (2016). A possible explanation for this might be the fact that risk matrices are easy to comprehend, easy to illustrate, do not need any special software and gives a clear screening of which risks are important to control. Risk registers and risk reports were other qualitative risk assessment methods used by the respondents, but these are simpler risk assessment methods and should be used in combination with more sophisticated qualitative or quantitative methods such as risk matrices or probabilistic risk analysis.

What is surprising is that that only three out of eight participants are considering correlations between risks in their risk assessment process. In addition to these three participants, another three participants consider correlations to some degree. Several reports have shown that the correlation between risks is of importance in order to attain relevant and accurate results (Chau, 1995; O’Connor and Kleyner, 2012; Peleskei *et al.*, 2015). This discrepancy could be a result of the difficulties of quantifying correlations between risks.

5.2 Monte Carlo simulations

As mentioned in the literature review, implementation of risk management concepts can be one of the main factors deciding if a project is successful or unsuccessful in achieving project objectives (Bissonette, 2016). Another study found that costs are underestimated in 9 out of 10 transportation infrastructure projects, with an average of 28% higher cost than estimated (Flyvbjerg, Holm and Buhl, 2002). When we consider that Senesi, Javernick-Will and Molenaar (2015) have concluded that probabilistic risk analysis, such as Monte Carlo simulations, can help better manage project schedules, project costs, and project risks, it is surprising to see that Monte Carlo simulations or other probabilistic risk assessment methods are seldom used in the infrastructure industry in Sweden today. Seven out of eight participants were familiar with Monte Carlo simulations, five out of eight were positive to Monte Carlo simulations, but still, only one out of eight have added these simulations into their risk management toolbox. What is also surprising is that all five consultants were positive to Monte Carlo simulations, whereas none of the three employees of the Swedish Transport Administration believes Monte Carlo simulations create any extra value for them. There are several possible explanations for this. Firstly, the clients are those who in the end have to take the extra cost for the work needed to conduct a detailed Monte Carlo simulation. The results of this study show that the clients do not believe the extra value of Monte Carlo simulations outweighs the extra costs. As two of the participants explained, they did not believe Monte Carlo simulations would reduce the uncertainty to a degree that could defend the costs.

Another possible explanation for this difference in perceived value of Monte Carlo simulations can be differences in experience and education. Out of the eight participants, five have the same education from the same university in Sweden, and all participants have four or more years of experience with risk management in the infrastructure industry. This points in the direction that the different opinions do not come from different backgrounds, but rather as a result of seeing the problem at hand from different sides of the table.

A third possible explanation why Monte Carlo simulations are not used in the infrastructure industry in Sweden today might be that no one wants to bear the risk of implementing a potential costly method without seeing others succeeding with that method first. Considering that there exist multiple software programs able to do probabilistic risk analysis today, one of the participants points out that it is essential to choose the right software combination to allow smooth transmission of data between different software programs used. The clients usually have their preferred software programs for scheduling and budgeting, and it might be difficult to change software programs to allow new risk assessment methods if they are pleased with what they are using today.

Monte Carlo simulations can help better manage project schedules, project costs, and project risks according to the literature. Monte Carlo simulations will not eliminate risk in a project but should provide a better basis for managers to make the right decisions by visualizing all possible scenarios (Khedr, 2006; Kwak and Ingall, 2007; Senesi, Javernick-Will and Molenaar, 2015). Several reports have shown that the choice of how to describe the uncertainty of the random variables is the critical part of the Monte Carlo analysis, as the quality of the output is a direct consequence of the quality of the input

(Loizou and French, 2012; O'Connor and Kleyner, 2012; Smith, Merna and Jobling, 2013). It is possible, therefore, that the Monte Carlo method seems like a complicated and advanced method, which to some extent is true. The mathematical reasoning behind the Monte Carlo simulation might be complicated for managers to comprehend, but as mentioned in the literature review, there are four commonly used probability distributions within risk analysis that are applicable to most random variables relevant to risk management (Smith, Merna and Jobling, 2013). All of these are easy to comprehend, easy to apply to practical cases, and all this can be done visually with the help of specific software programs.

The results of this study indicate that most people in the industry use statistics as a part of their input for the risk analysis, while all eight participants use experience as input. These findings imply that it should be possible to collect and structure relevant input for Monte Carlo simulations and therefore utilize the possible benefits from the results of these simulations. The complexity behind the mathematical part of the Monte Carlo simulations suggests that the risk manager responsible for the Monte Carlo simulations should have comprehensive knowledge of risk management and a mathematical understanding of the Monte Carlo method. However, this does not mean that everyone in the organization need to have this knowledge. As long as the risk manager is able to clearly communicate the assumptions behind the model and what implications these assumptions have for the results, Monte Carlo simulations should reduce the uncertainty facing the project and contribute to a better understanding of the risks.

6 Conclusions

This last chapter of this report summarizes the findings and gives answers to the research questions presented in Section 1.2.

6.1 Risk management in the infrastructure industry

The purpose of the current study was to determine how risk management is performed in the infrastructure industry in Sweden today and how Monte Carlo simulations can reduce uncertainty in infrastructure projects. This study has identified that ISO 31000 is commonly used within the infrastructure industry in Sweden and that risk management is considered an iterative process that should proceed during the whole project life cycle. Risk analysis is one out of eight parts of the ISO 31000 risk management process, and this study shows that the most frequently used risk analysis tool is without doubt risk matrices. Risk matrices are very useful to rank all risks facing a project but should be used more as a foundation for further risk analysis than as a risk analysis tool by itself. Another interesting finding is that the infrastructure industry only partially considers correlations between risks, although the literature concludes that correlations are of importance to attain relevant and accurate results.

One of the findings of this study is that probabilistic risk analysis, such as Monte Carlo simulations, seldom are used in the infrastructure industry. In general, therefore, it seems that the risk managers in Sweden put a higher emphasis on qualitative risk assessment than quantitative risk assessment. The study has found that risk consultants generally are favorable to the implementation of Monte Carlo simulations into their risk management process, whereas the clients are skeptical of the benefits Monte Carlo simulations add compared to the associated costs. The literature review points at several benefits of including probabilistic risk analysis into the risk management process and that Monte Carlo simulations can be implemented without comprehensive knowledge of the mathematical models which are the foundation of the method. Most random variables relevant for risk assessment can be approximated by a few simple probability distributions and can be generated either based on statistics or subjective data. An implication of this is that Monte Carlo simulations can be implemented as a quantitative risk analysis tool without too many difficulties in most organizations. All that is needed is a risk manager with the essential knowledge of the inputs and outputs of the method.

As this study has identified, the quality of the output of a Monte Carlo simulation is a direct result of the quality of the input. This implies that an organization that can structure their random variables as appropriate probability distributions should be able to utilize Monte Carlo simulations to reduce uncertainty in their projects. The ability to include correlations between risks into the Monte Carlo simulations is another feature that should give a better understanding of uncertainty. The statistical nature of the output of a Monte Carlo simulation gives risk managers the opportunity to better visualize and explain the risks involved in a project to managers, and this should contribute to better understanding of uncertainty and in the end better decisions for the organizations.

The insights gained from this study may be of assistance to risk managers who want to gain new knowledge within probabilistic risk analysis. Risk managers who see the possibilities and have the knowledge to avoid the pitfalls of Monte Carlo simulations should be able to get ahead of the rest of the industry when assessing the uncertainty associated with projects. Furthermore, this study leads to a recommendation to both consultants and the Swedish Transport Administration to start build a database with risk data from historical, current and future projects, including data of correlations between risks. This data can become valuable as it can help define input to Monte Carlo simulations in future projects.

"If you don't risk anything, you risk even more." – Erica Jong

6.2 Limitations and future research

A limitation of this study is the number of respondents and the homogenous group that participated in the interview study. Further research is required in order to quantify the possible benefits of probabilistic risk assessment within the infrastructure industry. The question raised by this study is why probabilistic risk analysis is seldom used in the industry today, although prior studies in the area show several possible benefits. Further research should focus on case studies to better understand the value of Monte Carlo simulations in the infrastructure industry. Especially within scheduling and budgeting, Monte Carlo simulations seem to have unredeemed potential.

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Appendix: Interview guide

Interview: Risk management in the infrastructure industry
This interview is a part of my master's thesis work in the master's programme Design and Construction Project Management at Chalmers University of Technology. The thesis work is supported by Norconsult Göteborg (project and construction management). The interview answers will be anonymized in the report.

Questions about the master's thesis:
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A. Context

1. Name
2. Age ☐20-35 years ☐36-50 years ☐50+ years
3. Education
4. Work experience, job title
5. For how many years have you worked here?
   ☐0-3 years ☐4-9 years ☐ 10+ years
6. How many years of experience of risk management?
   ☐0-3 years ☐4-9 years ☐ 10+ years
7. What kind of projects do you work with?
8. Your role in these projects?

B. Risk management

1. How would you describe risk within infrastructure projects?
2. Standard/method?
   a. ISO31000, PMI etc.
   b. Are these standards/methods used as they are written, or are they adapted?
3. Quantification or risk (or uncertainty)?
   a. Method?
   b. Tools?
   c. Statistics?
   d. Experience?
   e. Correlations?
4. Software?
5. During the whole project life cycle or only in some phases?

C. Monte Carlo simulations

1. Do you know what Monte Carlo simulations (MCS) are?
2. If yes:
   a. How do you use MCS?
   b. To what extent do you use MCS?
   c. In what phases do you use MCS?
   d. Software for MCS?
3. If no:
   a. How do you quantify risks?
4. Other probabilistic risk analysis methods or simulations?

D. Future of risk management

1. Areas of development within risk management?
2. What are needed to allow these changes?
   a. ☐Education
   b. ☐Time
   c. ☐Management support
   d. ☐Economy
   e. ☐Prioritization
   f. ☐Other: ____

E. Closure

1. Something you would like to add?
2. Can I contact you at a later stage if needed?
3. Do you know others that can be of value for this study?
4. Thank you!