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Master Thesis

Applied Mathematics

Quantifying risks to security of supply for 100% hydrogen in built-environment using Structured Expert Judgement

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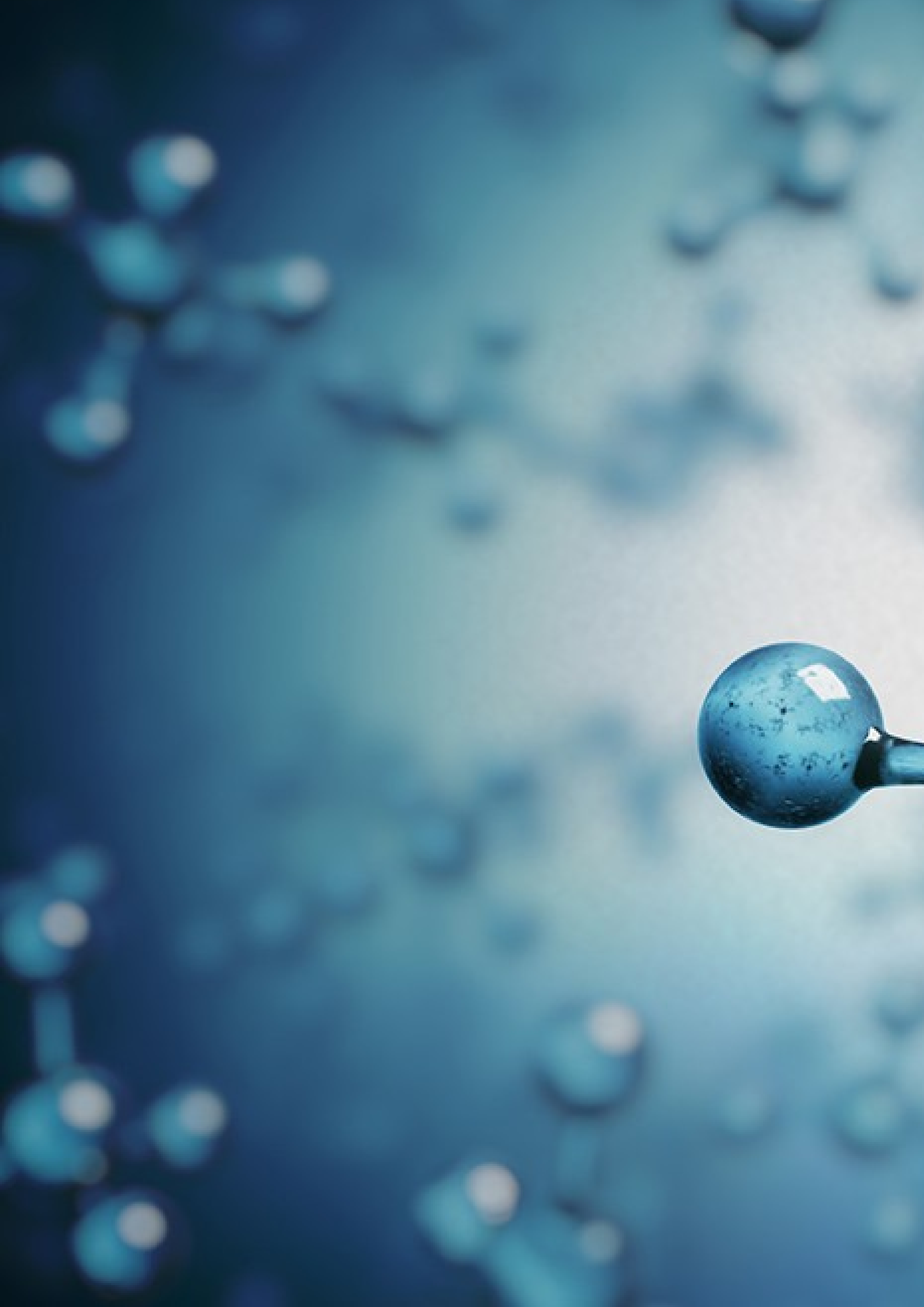

Quantifying risks to security of supply for 100% hydrogen in built-environment using Structured Expert Judgement

by

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‘All models are wrong, but some are useful.’
George E. P. Box

Abstract

In this thesis, we explore a proposal from Stedin that advocates heating the city of Stad aan 't Haringvliet with hydrogen rather than natural gas. Switching from natural gas to hydrogen presents plenty of unknown factors which must be properly evaluated for an accurate and realistic risk picture, including the danger of running out of hydrogen. The objective of this study is to examine the security of a 100% hydrogen supply in city buildings. For this MSc thesis, the security of supply is defined as a reliable and uninterrupted supply of hydrogen for heating purposes. We explore security of supply by evaluating the risk to it.

To achieve this goal, we construct a hydrogen supply system using Stedin's criteria. The Classical Model for Structured Expert Judgement and the Bayesian Network are the two mathematical techniques we use to evaluate the risks. The lack of acceptable data makes the task of quantifying the risk to supply much more difficult in this regard. Expert opinion remains the sole trustworthy source of information in these conditions for quantifying uncertainty. However, expert opinion should be validated using objective performance measures. As a result, we adopt the Classical Model for Structured Expert Judgement. The resulting uncertainty distributions of the Structured Expert Judgement research are then integrated in a Bayesian Network that models the uncertainty within the hydrogen supply system. Bayesian Networks are an effective tool for visualizing a domain's probabilistic model, examining all random variable interactions, and inferring probability for scenarios based on available data.

The findings of Structured Expert Judgment reveal that there will be an forecast 114 minutes of not enough hydrogen in the buildings of Stad aan 't Haringvliet in the first year of realizing Stedin's pilot, given the event that there will be a lack of hydrogen in Stad aan 't Haringvliet. Moreover, the security of supply is expected to not be achieved with an estimated probability of 0.06839 for the first year of realizing this pilot. Furthermore, failure rates for each component of the hydrogen supply system have also been quantified using the Classical Model, and one or more mitigations has been proposed for each component. Quantifying the Bayesian Network with the distributions for each component of the hydrogen supply system that resulted from the expert judgment study, yield distinct results than experts' aggregated distributions on the estimated probability and the duration of not meeting the energy demand. The results show that the best estimated probability for not having enough hydrogen in the buildings equals 0.2067 and when we consider the event of having a lack of hydrogen in the buildings, the best estimated time for how long this will last equals 3.135 minutes in the first year of realizing Stedin's pilot.

Preface

This thesis represents the end of my six-year career as a mathematics student. While it symbolizes the finish of the voyage, it surely does not characterize the beginning. Surprisingly, I always wanted to go to Delft University of Technology when I was in middle school. I began to develop an interest in mathematics in middle school, and after graduation, I was undecided about whether I wanted to pursue a degree in Theoretical Mathematics at Leiden University or Technical Mathematics at Delft University of Technology. I ultimately chose Leiden University and completed my bachelor's degree there. While I spent the first three years of my trip at Leiden University, I quickly realized that I was more interested in the applied side of mathematics. As a result, I did not pursue my studies at Leiden University. I enrolled at Delft University of Technology for the master in Applied Mathematics, and I can confidently say that the courses I took piqued my interest, and that I loved the program far more than I had anticipated.

Completing this thesis is the final step in earning my Master of Applied Mathematics. This master thesis was a cooperation with Stedin, a regional grid operator in the Randstad conurbation in the Netherlands. The transmission of electricity and gas to nearly 2 million residential and industrial customers is the responsibility of Stedin. The network operator's territory includes three of the four major cities of The Hague, Utrecht, and Rotterdam, as well as the Port of Rotterdam. Together with the research institute Kiwa NV, a Dutch company for testing, inspection and certification, they have set up a pilot on how the gas network of Stad aan 't Haringvliet can gradually switch from natural gas to green hydrogen.

At first the main problem and the set up of this research was unclear, but after many conversations with Stedin and my supervisors, reading in many related studies, thinking about methods on how to tackle the problem, we managed to create a structure for the research and the main problem became more clear. This was a special learning process for me in the field of doing research and it helped me to boost my research abilities significantly.

One of the lessons I will remember is that conducting research involving several areas of expertise is a difficult task that needs good communication, a clear organization, precise formulations, and a certain amount of confidence. For a long period of time, this looked to be quite tough for me, but I can now state that I have made progress.

Acknowledgements

I received a number of help and guidance throughout creating this Master project.

First and foremost, I want to express my gratitude to Dr. Tina Nane, my supervisor, whose mathematics expertise was crucial in developing the research objectives and methodology. Your informative remarks encouraged me to improve my thoughts and raise the quality of my work. I would also like to express my gratitude for your patience and for all of the possibilities you have provided me to pursue my studies. You are truly the most caring person I know.

I would like to acknowledge my other two supervisors, Prof. Ad van Wijk and Dr. Samira Farahani for their collaboration and making it possible to combine a project from Stedin with mathematical concepts.

Next, I would like to thank Frank van Alphen, Albert van der Molen, and Michel Honselaar. Their knowledge and expertise in natural gas and hydrogen (systems) was of great interest for this project and helped me with providing tools that I needed to decide the proper path and finish my thesis successfully.

Lastly, I would like to thank the experts that took part to one of the mathematical methodology that has been used in this research: Sjoerd Delnooz, Rob Stikkelman, Jurriaan Peeters, Harm Vlap, Martijn Duvoort, and María del Mar Pérez-Fortes. Without them I was unable to finish this research.

Esma Özdemir,
April, 2022.

Notation

Acronyms

CM	Classical Model
SEJ	Structured Expert Judgement
DM	Decision Maker
EWDM	Equal-Weighted Decision Maker
PWDM	Performance Weighted Decision Maker
OPWDM	Optimised Performance Weighted Decision Maker
BN	Bayesian Network
EBN	Extended Bayesian Network
DAG	Directed Acyclic Graph
DBN	Discrete Bayesian Network
CBN	Continuous Bayesian Network
HBN	Hybrid Bayesian Network
NPBN	Non-Parametric Bayesian Network

Symbols

N	Number of consulted experts
e	Index of the experts
α	Threshold
m	Number of calibration questions
$X(i)$	Percentile for the i-th calibration question
q_i	Value of the i-th% quantile
p	Theoretical Probability vector
V	Set of vertices/nodes
E	Set of edges/arcs
$Pa(A)$	Set of the parents of node a
$An(a)$	Set of the ancestors of node a

Functions

$w(e)$	Global weight of expert e
$C(E)$	Calibration score of expert e
$I(e)$	Information score of expert e
$\mathbb{1}_\alpha(\cdot)$	Indicator function which indicates if its argument exceeds a certain threshold α
W	Sum of all the global weights
$CS(e)$	Combined score of expert e
P	Probability mass function
$I(S,P)$	Relative information of S with respect to P

Distribution

S	Empirical sample distribution
$U_{[a,b]}$	Uniform distribution on the interval $[a,b]$ with $-\infty < a < b < \infty$
$\ln(U_{[a,b]})$	Log-uniform distribution on the interval $[a,b]$ with $0 < a < b < \infty$
$Wei(a,b)$	Weibull distribution with scale parameter $a > 0$ and shape parameter $b > 0$
$Ber(a)$	Bernoulli distribution with parameter $0 < a < 1$

Terms

Hydrogen	Green hydrogen or hydrogen with a green certificate, unless stated otherwise
Other types of hydrogen	Hydrogen without a green certificate
Mechanic	Refers to different specialized role
SEJ research	Research performed using Structured Expert Judgement
BN research	Research performed using Bayesian Network without the extension that is mentioned in the thesis
EBN research	Research performed using the Extended Bayesian Network

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Chapter 1

Introduction

In this thesis, we look at a proposal from Stedin that involves using hydrogen instead of natural gas to heat the city of Stad aan 't Haringvliet for the same objectives. The goal of this thesis is to assess the risk to security of 100% hydrogen supply in the buildings of the city. We employ two mathematical methodologies to evaluate risks: the Classical Model for Structured Expert Judgment and the Bayesian Network.

1.1 Motivation for Research

In this thesis we focus on the risk to security of supply, that is, the risk of not being able to provide reliable and uninterrupted supply of hydrogen for heating purposes. It is of great interest to use hydrogen as a energy carrier since it contributes to clean energy transitions. With this respect, the lack of (appropriate) data makes the endeavour even more challenging. In these circumstances, expert opinion remains the only reliable information of data points to quantify uncertainties.

Therefore, we propose a method in which experts' judgments are subjected to the same quality control as any other type of data. We aim to validate expert opinion, and use objective performance measures to aggregate assessments. The method is called the Classical Model for Structured Expert Judgment, which has been developed at Delft University of Technology. For more than 30 years, the method has been applied in a broad range of areas, including nuclear industry, investment banking, environmental sciences (such as climate change), dike safety, natural disasters, volcanology, and health care [1].

The Classical Model has proven its superiority among other expert judgement methods. The validation step enables the comparison of various weighting schemes and allows for the best possible combination of expert assessments. The method also allows for a rigorous yet transparent process that ensures high quality expert data and reproducible results.

The Classical Model can be applied as a standalone method to quantify uncertainty for crucial quantities of interest. In section 1.2 two crucial quantities of interest are addressed, namely the probability of not meeting the security of supply and the corresponding duration. Alternatively, expert input would then be integrated with any available data, in order to quantify the risks of the standalone risk system.

Next, we aim to model multivariate uncertainty distributions. By utilizing the results from the the Structured Expert Judgement research in a probabilistic model called Bayesian Network, we can achieve this. Bayesian Networks are a powerful tool for visualizing the multivariate distributions, for reviewing the random variables interactions, and for updating probabilities for scenarios based on existing information [2].

1.2 Aim of the Research

The main goal of this thesis is to quantify the risks to security of supply for 100% hydrogen in the homes of Stad aan 't Haringvliet. We model a hydrogen supply system according to Stedin's premises in order to attain this aim. This system is more sophisticated in practice. However, due to the scope of this thesis we condensed it to a level appropriate for a master's thesis by making many assumptions. We will concentrate on gaining answers to the following two research question:

1. How likely is it that there is not enough hydrogen in the buildings of Stad aan 't Haringvliet in the first year of realizing Stedin's pilot, in probability?

2. Consider the event of not having enough hydrogen in the buildings of Stad aan 't Haringvliet. How long do you expect this to last in the first year of realizing Stedin's pilot, in minutes?

1.3 Overview of the work

The structure of the master's research is discussed in this section. Figure 1.1 shows a flowchart that graphically depicts the organization of the work. In Chapter 2, we provide a brief introduction to hydrogen as an energy carrier, followed by a reasoning for its usage in the industry. In this chapter, two hydrogen studies are described, one of which will be the focus of this project. In Chapter 3 we construct a system and systematic event influence diagram for hydrogen supply according to the guidelines of Stedin. The components of the system and diagram as detailed as possible. In Chapter 4 we introduce relevant literature close to the subject of risk to security of supply and the methodology employed. Hydrogen is expected to replace natural gas and relevant literature on the risk to security of supply for natural gas will be provided. In Chapter 5 a presentation is given about the Classical Model for Structured Expert Judgement. The theory behind this model is explained in detail. In Chapter 6 an expert judgment study has been designed and conducted with 9 field experts. We present the elicitation protocol, and discuss the assessments of consulted experts for this research about hydrogen supply in the buildings in Stad aan 't Haringvliet. We report the performance of the experts and compare them which each other and the constructed Decision Makers (DMs), which aggregate experts' distributions using a set of weights including performance-based weights and equal weights. Afterwards the best performing Decision Maker is used to predict the quantification of the risks for this project of Stad aan 't Haringvliet. We wrap this chapter off by answering the questions of interest and making comparisons with the natural gas results as well as with the failure rate between each component. In Chapter 7 some notions of probability theory are presented. Moreover, an introduction to the second mathematical method of this research is given: Bayesian Network. The chapter ends with discussing different types of Bayesian Networks. In Chapter 8 we present the Bayesian Network analysis. First, the structure of the network is discussed, accompanied by its modeling. Next, an extension of the network is constructed. After performing the analysis, the findings are compared with each other and with the Structured Expert Judgement study. We complete this thesis with a conclusion and discussion.

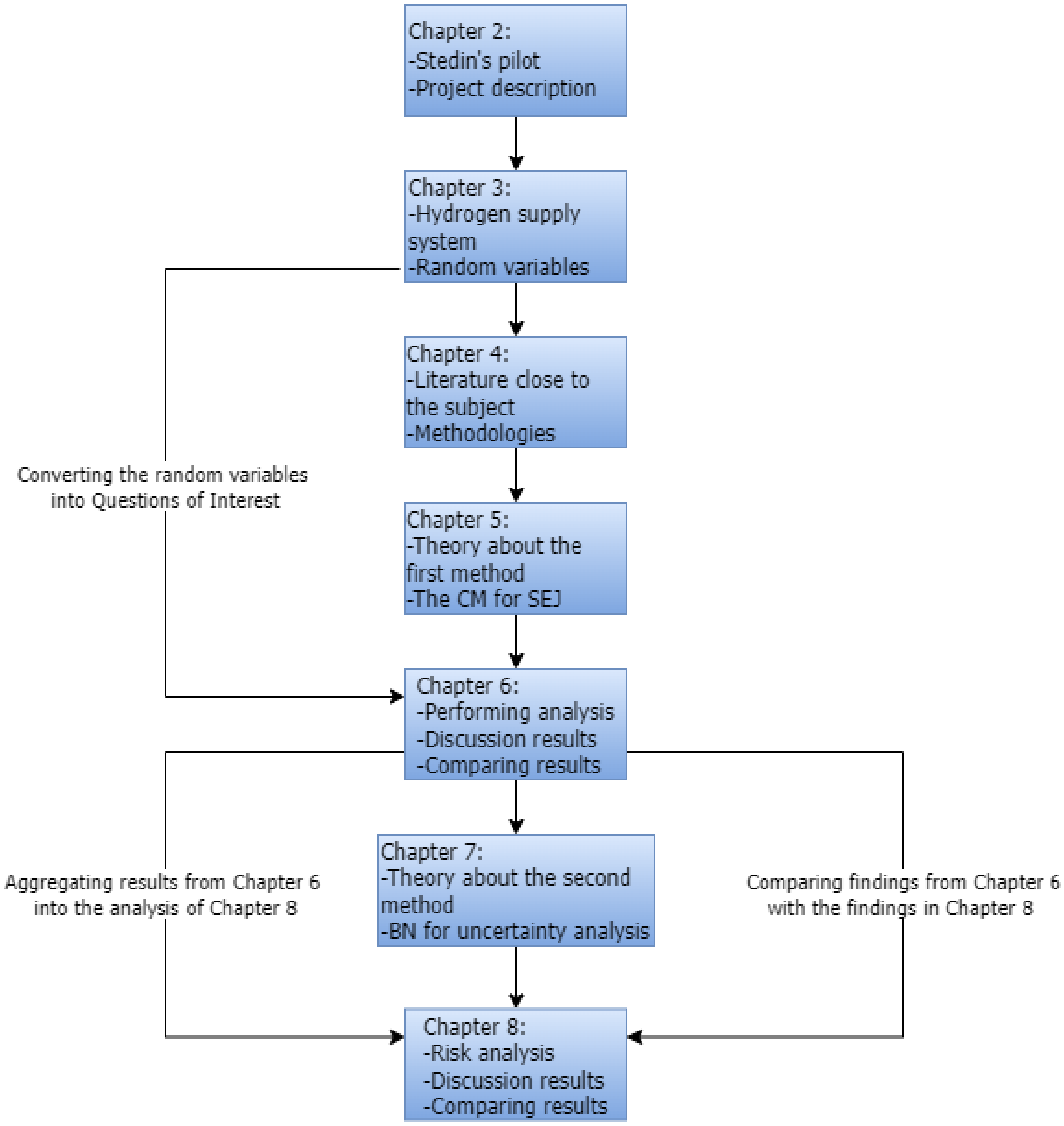

Figure 1.1: Flowchart illustrating the organization of the research.

Chapter 2

Project description

In this chapter we give a short introduction to the use of hydrogen as energy carrier, instead of traditional carriers, such as natural gas. Replacing natural gas by hydrogen involves countless uncertainties. As a result, looking into projects that employ hydrogen is quite interesting. Two hydrogen studies are discussed in this chapter: *Conversion project Uithoorn* by Stedin [3] and *Conversion project Stad aan 't Haringvliet* by Kiwa and Stedin [4]. The latter one will be the main focus in this thesis. The project concerns providing the city Stad aan 't Haringvliet with hydrogen instead of natural gas for the same heating purposes.

2.1 Hydrogen

In 1671 Robert Boyle discovered the most common element in our universe, namely hydrogen. In gas form, hydrogen is the lightest gas discovered so far [5]. However, in a high pressure environment hydrogen can have a high density of energy, which is almost three times as much as natural gas. Most of the hydrogen that is produced currently worldwide is done by generating natural gas or methane through steam reforming [6]. Steam reforming is a process that also generates carbon dioxide where carbon dioxide is not captured but emitted into the air, which have adverse effects for the atmosphere. Hydrogen produced by steam reforming is called grey hydrogen [6].

There are also processes where hydrogen is produced without harming our environment. Hydrogen produced by sustainable energy, such as wind and solar, is called renewable hydrogen, or more commonly, green hydrogen. The most popular form of producing green hydrogen is via electrolysis of water. In this process water molecules are split into hydrogen and oxygen molecules by utilizing green electricity. The excess in this process is oxygen, a substance which is not harmful for our atmosphere [7].

Instead of using natural gas, green hydrogen can be used for industrial applications. This is important since hydrogen plays an assistant role in being environmentally conscious. Applications such as high-temperature processes in industry, heavy transport, aviation etc. are still lacking good electrical solutions. Furthermore, the use of hydrogen in homes for heating purposes, results in reduced carbon emissions [7].

Nevertheless, transitioning from natural gas to hydrogen introduces a slew of unknowns that must be properly measured for professional organizations to get an accurate overall risk picture. It is critical, for example, to handle it with care during manufacture, transportation, storage, distribution, and usage. Because hydrogen is a lighter and more combustible gas than natural gas, it is of significant interest to learn more about how hydrogen interacts to existing gas pipeline networks, which are expected to be used for hydrogen transportation.

2.2 Hydrogen study

Various organisations in the Netherlands such as Stedin, Kiwa, and TNO have projects that focus on green hydrogen production, infrastructure, transport and applications. Here we present two projects concerning heating homes with hydrogen. Both are conversion projects from natural gas to hydrogen, where the first one takes place in Uithoorn [3], and the second one in Stad aan 't Haringvliet [4]. The latter project will be the main focus of this thesis, where we investigate the quantification of security risks of hydrogen supply.

2.2.1 Stedin: Conversion project Uithoorn

A project from Stedin that was focusing on the safety and reliability of natural gas to hydrogen conversion was started in Rozenburg and in The Green Village. A fresh pilot was contemplated after this experiment. The pilot took place at Uithoorn, a city in Noord-Holland province of more than 30,000 inhabitants. For a number of destroyed homes in this village the natural gas network was adapted to switch from natural gas to 100% green hydrogen.

In this pilot renewable electricity is produced with solar panels or wind turbines. As a result, the production of electricity is not constant, but oscillating. In order to balance the supply and demand, the gas network is considered as a solution. In this network the surplus of electricity can be converted into hydrogen. Moreover, excessive amount of hydrogen can be stored in the storage of the network. The hydrogen can be used through the existing large-mesh natural gas network and the central heating boilers provide heat to end users of Uithoorn.

Safety and security were primary priorities throughout the operation. To check for leaks, the team performed a nitrogen control first, then a helium control. Helium is similar to hydrogen in terms of physical features e.g., molecule size, but it is not combustible and does not react chemically with other chemicals. The operation of the conversion from natural gas to hydrogen was finished after extensive testing. For two weeks, the homes were heated with hydrogen. According to this study, converting from natural gas to hydrogen costs around one working day per facility employee per family.

2.2.2 Kiwa and Stedin: Conversion project Stad aan 't Haringvliet

Within the framework of the Convenant Groene Waterstofeconomie in South Holland, a plan is currently under development to supply hydrogen to Stad aan 't Haringvliet. The village Stad aan 't Haringvliet lies in South Holland, in the municipality of Goeree-Overflakkee and has about 1500 inhabitant [8]. The conversion is carried out by the management of regional grid operator Stedin and is expected to be completed in 2025.

In an average house, 80% of the energy demand arrives through gas pipelines. Stedin distributes natural gas to approximately 2.1 million small-scale consumers in the Netherlands. Natural gas is often used for space heating, hot tap water, and cooking.

With sustainable sources such as the sun and wind on one hand and the energy needs of the environment on the other hand, there exists a great inequality between production and consumption. Energy storage is necessary to efficiently utilize production facilities. Having a surplus of electricity is very expensive (about €200/kWh). If electricity is converted into a gaseous energy carrier, such as hydrogen, the surplus is more than one hundred times cheaper. From personal communication with an employee from Stedin, we need a storage with $\geq$ 70% storage capacity of hydrogen, which equals in this project to 26 MWh and 780 kg of hydrogen. In addition to extra energy, transport and distribution are also relevant aspects. In terms of energy, the natural gas distribution network supplies ten times as much energy and has approximately four times higher capacity than the electricity distribution network, but at the same cost. From this we can deduce that if we replace the gas with hydrogen gas, we will be most favorable in terms of energy supply and costs.

Alternatives have been proposed to natural gas, such as district heating and heat pumps. The conversion to hydrogen has advantages compared to these alternatives. For example, the historic character of Stad aan 't Haringvliet makes it difficult to install heat pumps. Space in the houses is limited and the necessary measures to for heat pomp installations are almost impossible to implement. District heating is also difficult, if only for the absence of a heat source and of large buildings with a central heat supply which are necessary to use district heating cost in an effective way. The idea of providing heat to Stad aan 't Haringvliet via hydrogen has been presented to the inhabitants and for the time being the inhabitants are not negative about the use of hydrogen. Conversion to hydrogen is therefore the best alternative to the existing natural gas network. It also meets the requirement of a reliable energy supply at socially acceptable costs, as required by grid operator Stedin.

The village Stad aan ‘t Haringvliet has a gas network that consists of a high-pressure section and a low-pressure section. The low-pressure section has a pipeline length of over 15 kilometers and serves over 600 connections, 15 of which are large consumers. Five district stations fuel the grid. The highest gas demand (natural gas) for small-scale consumption is now about 1,600 m^3n/h, whereas large-scale consumption is more than 200 m^3n/h. Natural gas is projected to be delivered at a rate of 2,000,000 m^3 per year, or 20 GWh per year.

An average household consumes 1.300 m^3 natural gas per year, where roughly 80% of the gas is used for heating up the home, 18% for hot water and 2% for cooking (furnace). Together with the fact that around 600 houses in Stad aan ‘t Haringvliet consume 780.000 m^3 natural gas per year. Since hydrogen has a higher energy density per unit mass, namely nearly three times that of natural gas [9], we can state that we need around 3×780.00 m^3 $=$ $2.340.000$ m^3 of hydrogen to meet this energy demand. Based on the estimates from literature [10], we assume that the production of 1 kg (or 11.1 m^3) of hydrogen via electrolysis requires 54.3 kWh of electricity to produce it via electrolysis. This means that the electricity required to generate the hydrogen demand for Stad aan ‘t Haringvliet equals

$$\frac{2.340.000}{11.1} \times 54.3 \text{ kWh} \approx 11.5 \text{ GWh}$$

approximately per year, if for 11.1 m^3 of hydrogen 54.3 kWh of electricity is required.

The present gas network’s high-pressure segment consists of an 8 bar pipeline of about 2 km on the village’s north side and a 2 bar pipeline of approximately 2.5 km along the village’s south and east sides. Along the 8 bar supply line, on the north side of the village, there is a suitable area for hydrogen generation. As a result, it makes sense to bring hydrogen to the village through the supply line on the north side, near the football field. Because the 2 bar network is fed from the south and east sides, it may stay operational during the changeover to natural gas delivery to the village. For a few big consumers, on the south side near Boomgaardsdreef, it is difficult to convert to hydrogen. Natural gas will continue to be supplied for these firms. Without a lot of additional plumbing, this is also technically doable. On the south side, there is a ’loose’ low-pressure network with only a few customers, fed by a single district station (a high-pressure connection set) which will not be converted to hydrogen.

We need to take a number of risks into account when we switch from natural gas to hydrogen, such as hydrogen leakages. A hydrogen leakage in the pipeline system can occur when there are holes in the pipeline. Both large holes (i.e. $\frac{1}{3}$ diameter of the pipeline) and holes smaller than < 5 mm diameter cause leakage [11]. Furthermore, a leakage can also be caused by rupture and brittle material of the pipeline. The pipelines in which hydrogen is transported are made of steel and have a diameter of 200 mm. In the distribution part where there is high pressure, steel and PE is used for the pipelines. PVC, PE, and copper are used for the low pressure in the distribution section. In the households we are dealing with pipes made of steel. The diameters vary from 15 to 200 mm.

Another aspect which has to be considered when accounting for the risks of changing to hydrogen is if the received hydrogen does have a good quality. That is, the received hydrogen is impure, i.e. it contains $\geq$ 0.0002% oxygen and $\geq$ 0.0005% water. However, this aspect is outside the scope of this thesis.

The process of conversion to hydrogen needs to take place in stages. According to [4] all distribution pipes may theoretically be cleansed in a short amount of time, namely one day. For two technicians, the time necessary for the conversion or replacement of the appliances, as well as the accompanying inspections on the meter set-up and indoor installation, are anticipated to be around 312 hours per connection. As a result, with the manpower available for all clients in a reasonable amount of time, it is not possible to modify the region in one go. Consequently, the conversion is broken down into a series of stages, with the distinction between the hydrogen and natural gas networks altering continually per day. Because every operation on the gas network has some risk, the number of divisions should be kept to a minimum. The goal is for a residence to be without gas for no more than one day throughout the conversion. The specifics are still being ironed out, but if a team of 20 specialists is available, the 600 connections are expected to be changed in 30 days. The separation between the hydrogen and natural gas networks will be shifted roughly 30 times, and the conversion process will then proceed across the area like 'a train'. In general, the conversion is divided into two stages. The four district feeding stations must also be modified in addition to the residences. This must be done in such a way that both the natural gas and hydrogen networks have sufficient supply capacity on a daily basis. Of course, this necessitates the required attention and calculations for the intermediary grid configurations' capabilities.

It is expected that nothing will change for inhabitants in terms of usage and comfort once the gas network and appliances in Stad aan 't Haringvliet have all been converted. It is hoped that the comfort and warmth of the homes would be as natural and trouble-free as when natural gas is used. The network and meter installations will be scrutinized with a keener eye than usual. Leaks will be searched more frequently, stations will be examined more frequently, and excavation activity will be supervised more closely, especially at the beginning. Residents may be able to transition to contemporary gas uses, such as the fuel cell, in the long run if hydrogen is distributed. In principle, there would be no need to connect to the power grid. For the time being, however, these are fantasies for the future.

Chapter 3

Project Stad aan 't Haringvliet

The major objective of this thesis is to quantify the risk to security of supply for 100% hydrogen in built-environment. In order to achieve this goal we model in Section 3.1 a system for hydrogen supply according to the guidelines of Stedin. In practice this system is more complicated. However, for to the scope of this thesis we simplified it to a level that suits a master project, by making several assumptions. After discussing the system, we construct an diagram that gives insight into the influences of each event in the hydrogen supply system. We end this chapter with Section 3.2 by specifying the components of the system. We introduce several random variables for each component and investigate which variables can be quantified using available data.

3.1 Starting point: Stad aan 't Haringvliet

Switching from natural gas to hydrogen involves numerous sources of uncertainty, which need to be appropriately quantified for an accurate overall risk picture. As mentioned beforehand, the scope of this thesis is quantifying risk to security of supply for 100% hydrogen in built-environment. More specifically, we investigate the following two research questions:

1. How likely is it that there is not enough hydrogen in the buildings of Stad aan 't Haringvliet in the first year of realizing Stedins' pilot, in probability?

2. Consider the event of not having enough hydrogen in the buildings of Stad aan 't Haringvliet. How long do you expect this to last in the first year of realizing Stedin's pilot, in minutes?

In Figure 3.1, the hydrogen supply system is given in the form of a chain, which we discuss now. In order to produce hydrogen by electrolysis, green electricity is required. Green electricity is electricity produced from renewable sources such as wind and solar and can be obtained with the help of wind turbines and solar panels. They have a significantly lower carbon footprint than fossil fuels like coal and gas. After producing green electricity, the process of electrolysis can start where water molecules are split into hydrogen at 30 bar and oxygen gas. Excessive amount of hydrogen can be stored in tanks at pressures of maximum 80 bar, which is first compressed by the compressor from 30 bar. Next, hydrogen's pressure needs to be reduced from 80 bar to maximum 40 bar, which is needed for the transport in the pipelines from outside Island of Goeree Overflakkee to Stad aan 't Haringvliet. These pipelines need to pass through the city gate station first, where the pressure is reduced to maximum 8 bar and then to maximum 100 millibar on street level. After the pipelines with hydrogen passes through the city gate station, the distribution of hydrogen through the pipeline system can start. The hydrogen flows through the system to the buildings.

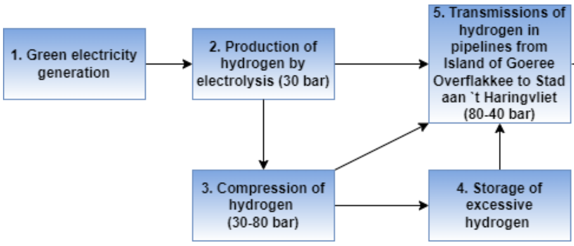

Figure 3.1: System for hydrogen supply.

Next, we consider Figure 3.2, where a systematic event influence diagram is given for the hydrogen supply, with events of interest and the consequences when a problem occurs. Each green component, which is marked with a number (and sometimes followed by an letter 'A') corresponds with a component in the system of hydrogen supply, see Figure 3.1. The red components correspond to the events that something goes wrong. Yellow colored components corresponds to the events that solve a problem regarding the hydrogen production or compression. The outcomes of the yellow colored components result either indirectly (i.e. when there is not enough green hydrogen stored) or directly (i.e. there is enough green hydrogen stored or using other type of hydrogen from tube trailers) for enough hydrogen supply for the process of transporting (node 4A).

In order to obtain a sufficient amount of hydrogen in the buildings (number 7), there should not occur any problems in the nodes denoted by number 4A, 5A, and 6A. When there is no green electricity production or the process of electrolysis is disturbed for some time, the supply system does not produce green energy in that time period. We can solve this problem by using hydrogen from the storage or even other types of hydrogen from tube trailers. When problems occur with the compression of green hydrogen, the produced green hydrogen cannot be used to supply the building from hydrogen. In order to still obtain a sufficient amount of hydrogen in the buildings, green hydrogen from the storage can be used in this time period, if there is enough green hydrogen stored. If there is not enough green hydrogen stored, other types of hydrogen can be used to supply the buildings with hydrogen.

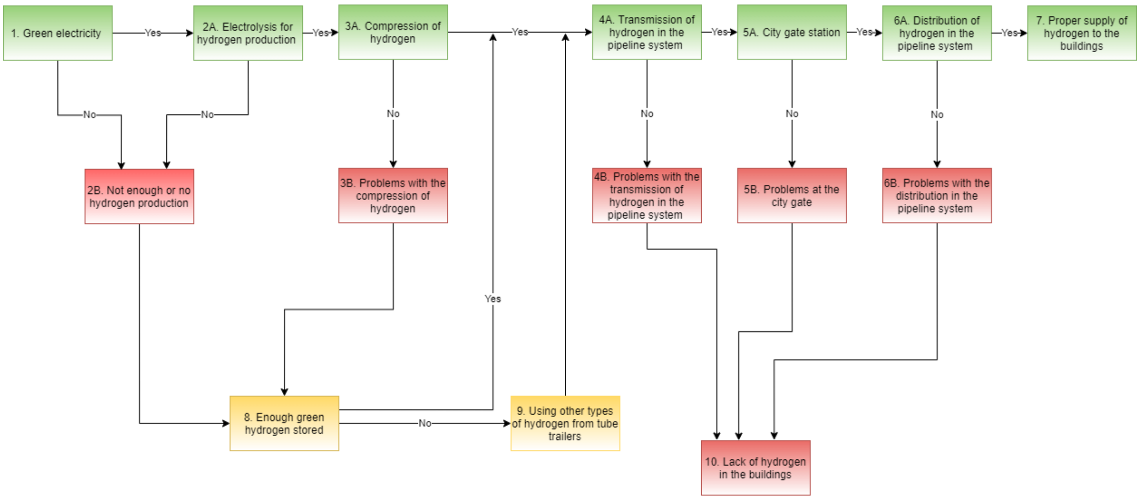

Figure 3.2: Systematic event influence diagram for hydrogen supply

3.1.1 Assumptions

In this project we made some assumptions about Stedin's pilot and the event sequence diagram in Figure 3.2.

1. In the systematic event influence diagram, we have the following steps for hydrogen production before entering the transmission network. First we use green electricity from the network and electrolysis to produce hydrogen. If there is no green electricity available, we use hydrogen from the storage. And if there is not enough hydrogen in the storage or there is an issue with the storage such that we cannot use enough hydrogen, we buy hydrogen from external sources (e.g., tube trailers). Then hydrogen enters the transmission network. This means that we always have hydrogen entering the transmission network (as shown in the diagram). In other words, any issues related to the electrolyser or compressor will not influence the hydrogen supply at the buildings in Stad aan 't Haringvliet and we do not need to include them in the risk model. Nevertheless, including them in the risk model and assuming that we do not always have enough tube trailers can provide more insight in the risk assessment. Therefore, as a modest extension of the system, we will take a closer look at it in the risk model given in Chapter 8.

2. The first component in Figure 3.2 is not only about pure green electricity, i.e. electricity produced by renewable resources, but also electricity that has a green certificate. A green certificate is a marketable product that certifies whether electricity was produced using renewable resources [12].

3. According to personal communication with Stedin, the electrolysis will be connected to the electricity grid and not directly to a sun or wind farm. Here we consider all the energy on the Island of Goeree Overflakkee and this one is about 70% sustainable per year. This means that the energy comes about 70% from sources that can maintain our current energy needs without dam-

aging the future generations [13]. It is expected that more sustainable capacity will be added to the island in the near future, so that the share will increase. The Goeree Overflakkee area produces much more sustainable energy (sun and wind) than it consumes. In this project we consider therefore wind turbines that produce hydrogen directly and electrolyser linked to the electricity grid (or directly linked to a solar park).

4. Enough green electricity means that we do not have to use hydrogen from the storage. Enough green hydrogen capacity means that we do not have to use other types of hydrogen. Other types of hydrogen are e.g. black hydrogen, grey hydrogen, blue hydrogen, yellow hydrogen etc. Hydrogen of these types are not produced using electricity generated from renewables. In emergency situations we are going to tap another power. For example, hydrogen that comes from industry. This is expected to happen about once every 10 years according to personal communication with Stedin.

5. Problems with compressing hydrogen means that the compressor machine fails to compress the hydrogen at 30-50 bar to 80 bar.

6. The hydrogen storage should contain at least 70% of the storage capacity. Any percentage less than 70% corresponds to the event of not having enough hydrogen stored.

7. A pressure failure means that the hydrogen does not have the required pressure value in that stage of the system, but a value below the required threshold. (The pressure value of hydrogen can only drop after compressing hydrogen.)

8. It is possible that when hydrogen is mixed with the odorant, that this does not go well. A small amount of odorant can be added in proportion to the hydrogen volume. When a leak occurs, the odorant is barely smelled and this can have problematic consequences.

9. A lack of hydrogen in the buildings means that the heating purposes in the buildings are not achieved. Either the compressing stage is not working, i.e. the lack of heating is a result of the compressing stage, or the system is prone to leakages.

3.2 Component specification for hydrogen supply system

In this section we specify the components of the chain for hydrogen supply, see Figure 3.1. For each component we make clear what could instigate risks tied to the component and what could detect or fix the corresponding problem. The consequences of something going wrong in the process for hydrogen supply can be seen in Figure 3.2. Furthermore, we also quantify random variables to the corresponding components which will be specified more in Table A.1 of Appendix

A. The quantification of the random variables will be explained at last. Note that for the sake of this project we reduce the scope of listing the possible problems and events that would solve these problems. This means that we will not discuss every possible event that could instigate a risk for hydrogen supply with heating purposes and the corresponding event that would prevent this risk of happening. For example, the electrolysis process of hydrogen itself is quite complex, and its complexity will not be accounted for in this work in its fullest detail.

Component 1: Green electricity generation
Not producing electricity also results in not producing green hydrogen. This can happen in general when there is not enough renewable energy sources such as wind, solar, photovoltaics, hydro, biomass and geothermal [14]. For this project we only consider the renewable energy sources wind and solar. Another problem could be the failure of wind turbines or solar panels as possible reasons for not producing green energy. In this project we take the following two events into account.

$A1$: Wind turbines production;
$A2$: Solar panels production;

Component 2: Production of hydrogen by electrolysis
When the process of electrolysis fails, there will be no green hydrogen production either. This can occur in general when there is a problem at the components of the electrolysis process: stack, reverse motion, electricity convention, and ventilator. The consequence that we consider in this project is that the pressure of hydrogen is not at 30-35 bar after the process of electrolysis. Therefore we consider the following event in this project.

$B1$: Not enough or no green hydrogen production.

Component 3: Compression of hydrogen
A problem that can occur is that the compressor machine fails to compress the hydrogen from 30 bar to 80 bar. When this problem occurs, a mechanic* needs to solve the problem regarding the pressure of hydrogen in the compressor. Therefore, we consider two events.

$C1$: Wrong pressure of hydrogen in the compressor;
$NC1$: Mechanic fixes issues with pressure of hydrogen in the compressor.

Component 4: Storage of excessive hydrogen
A problem that can occur at the storage is that there is not enough green hydrogen stored, i.e. less than 70% of the net storage capacity. In that case, other types of hydrogen have to be used in order to supply the buildings with hydrogen. Another problem taken into account are the sensors that are measuring leakage in the storage, or which can contain an error. We need mechanics to fix the leakage

*In this thesis we use a generic term mechanic, which refers to different specialized roles.

and sensors if these problems occur. In order to quantify these problems, the following events are taken into account in this project.

- $D1$: Green hydrogen storage;
- $D2$: Leakage in the storage;
- $ND2$: Mechanic fixes issues with leakages;
- $D3$: Sensors that measure leakage in the storage contain an error;
- $ND3$: Mechanic fixes issues with the sensors;
- $D4$: Using other types of hydrogen.

Component 5: Transmission of hydrogen in the pipelines system from Island of Goeree Overflakkee to Stad aan 't Haringvliet
We assume that the problems occurring in the process of the transmission of hydrogen in the pipeline system are similar to the problems occurring in the process of transmission of natural gas in the pipeline system. We take the following three problems into account. Problems at the pressure management of green hydrogen from the compressor or storage to the transmission network may occur, or problems at the pressure management of other types of hydrogen from tube trailers may occur, consequently the required hydrogen pressure from 80 bar may not be reduced to 40 bar. When there is a problem with the pressure of hydrogen while transporting or there is hydrogen leakage, we need mechanics to solve those problems. This reduces to the following events.

- $E1$: Wrong pressure of hydrogen in the transmission pipeline system;
- $NE1$: Mechanic fixes issues with pressure of hydrogen;
- $E2$: Hydrogen leakage in the transmission pipeline system;
- $NE2$: Mechanic fixes issues with leakages;

Component 6: City gate station of Stad aan 't Haringvliet
A risk that we want to avoid is that the pressure in the pipeline system is not reduced correctly from 40 bar to 8 bar. Another problem that could occur is that there is in the pipeline system a leakage. In order to detect leakage, hydrogen is mixed with odorant. If there occurs a problem with mixing hydrogen with the odorant or there is a pressure failure of hydrogen in the city gate station, we need mechanics to solve those problems. Therefore it is convenient to consider the following events.

- $F1$: There arises a problem in mixing hydrogen with the odorant;
- $NF1$: Mechanic fixes issues with mixing of the odorant;
- $F2$: Wrong pressure of hydrogen at the city gate station;
- $NF2$: Mechanic fixes issues with the pressure of hydrogen at the city gate station.

Component 7: Distribution of hydrogen in the pipeline system
We assume that problems occurring in the process of the distribution of hydrogen in the pipeline system are similar to the problems occurring in the same process

for natural gas. We take the following problems into account in this project: problems at the pressure management may occur. Consequently the require hydrogen pressure at street level, which is 100 millibar, may not be attained. Another problem is that there occurs a leakage around the hydrogen pipeline system. This means that when there is a hydrogen leakage, sensor failure, or hydrogen pressure failure in the pipeline system at street level, we need mechanics to solve these problems. This yields us to consider the next six events.

$G1$:	Leakage in the distribution pipeline system;
$NG1$:	Mechanic fixes issues with leakages;
$G2$:	Sensors that measure leakage in the distribution pipeline system contain an error;
$NG2$:	Mechanic fixes issues with the sensors;
$G3$:	Wrong pressure of hydrogen in the pipeline system at street level;
$NG3$:	Mechanic fixes issues with the pressure of hydrogen in the pipeline system at street level.

Component 8: Hydrogen in the buildings

At this stage, the hydrogen should go to the buildings. A problem that may occur here is directly the overall problem, which we address with the whole system, see Figure 3.1. A possible problem that could occur is that the right pressure is not attained, namely 25 millibar. The final consequence, which is directly also the main focus of this project is that the buildings do not receive hydrogen (for a given time period). We need a mechanic when there is a pressure failure of hydrogen in the buildings. The following events are considered.

$H1$:	Hydrogen pressure at the buildings;
$NH1$:	Mechanic fixes issues with the pressure of hydrogen at the buildings;
$H2$:	Lack of hydrogen in the buildings, in probability;
$H3$:	Lack of hydrogen in the buildings, in time.

3.2.1 Distributions assignment to the random variables in Table A.1

The uncertainty regarding the events listed in Section 3.2 is quantified using random variables. Discrete random variables assume only a finite number of possible states. A continuous random variable assumes to take an infinite number of possible values. In Table A.1 of Appendix A we see that some random variables are discrete and some are continuous. For example, B1 can only take the values 'enough capacity' and 'not enough capacity', which both can be converted to a numerical expression. The random variable A1 is continuous because the amount of electricity production can take an infinite number of possible values. A random variable's distribution defines how the probabilities are distributed over the random variable's values. The random variables in Table A.1 are assigned a distribution. Some variables are assumed to follow known distributions, whereas other random variables have an unknown distribution. To quantify those distributions, we use Structured Expert Judgement, which we discuss in Chapter 5.

The first four random variables are assigned a distribution with their corresponding parameter. We shortly discuss how we assigned the distributions and parameters of the random variables from Table A.1.

Combining the information from papers [15], [16], and [17], it is justified to assign the random variables A1 and A2 with the Weibull distribution with scale-parameter 0.8 and shape-parameter 216. These Weibull parameters are obtained from three different methods from SOlar radiation DAta (SODA) database for typical and grouping three years, namely 2004, 2005, and 2006. The first method uses the Maximum Likelihoods; the second method obtains the parameters using Moment estimators; and the third method obtains it graphically.

The random variable B1 can have two outcomes, either 0 or 1. Outcome 0 corresponds to the event where we do not have enough or no green hydrogen production, where 1 corresponds to enough green hydrogen production. Therefore this random variable is Bernoulli distributed. According to personal communication with Stedin we have with probability 0.3 not enough green hydrogen production via electrolysis.

Random variables about pressure, i.e. C1, E1, E2, F2, G3, H1, are discrete random variables with two possible outcomes. They either have a pressure-value described in Section 3.2 or they do not have that pressure-value. Therefore these random variables are Bernoulli distributed. The parameters of the random variables are unknown, with exception of C1. According to study [18] the probability of a failure for compressing the hydrogen by a switch fault and switch delayed operation is small, namely 3.06×10^{-2}. Therefore the parameter assigned to the distribution of the random variable C1 equals the probability of having a failure for compressing the hydrogen by switch fault and switch delayed operation, i,e. the parameter is fixed at 3.06×10^{-2}.

The random variable D1 is about the quantity that green hydrogen is stored. From personal communication with Stedin, we know that this quantity should be at least 70%, i.e. at least 70% of the storage should contain hydrogen. This means that this random variable, D1, is Bernoulli distributed with two outcomes: either there is more than 70% hydrogen stored or not.

The random variables about leakages such as D2, E2, and G1 are discrete random variables with two outcomes. They are either 0, which corresponds to the event when there is not a leakages, or they equal 1, which corresponds to the event when there is a leakage.

The next random variables are also Bernoulli distributed, D3, D4, F1, and G2. These events correspond to outcome 0: error in sensors, using other types of hydrogen, and there arises a problem in mixing hydrogen with the odorant. The complementary events correspond to outcome 1.

Quoting the paper 'A comparative study of odorants for gas escape detection of natural gas and hydrogen' [19]:
'Our work provides evidence that firstly, the odorants currently used within natural gas will have a similar effectiveness in allowing escape detections when used with hydrogen. Secondly, that small escapes of hydrogen are detectable in a comparable way to a natural gas escape in an equivalent room volume. These conclusions can be considered robust as they were demonstrated by two different methodologies using very different approaches.'
We can conclude from this study that the probabilities for F1 and NF1 in the natural gas case can also be used for the hydrogen case.

The lack of appropriate data makes the distribution of some random variables unquantifiable. The only reliable knowledge source remains at the experts opinion in order to quantify these uncertainties. More information about the distributions (and parameters) of the random variables from Table A.1 are derived with the help of Structured Expert Judgement, see Chapter 5.

Chapter 4

Security of energy supply

As hydrogen is sought to replace natural gas, we now inquire about the security of natural gas supply. One of the goals is to compare the quantified risk for hydrogen to that for natural gas. In this chapter we give a formal introduction to the reliability of supply for natural gas and hydrogen, where the first one will be the main topic. First, we provide context to our setting by introducing Stedin's setting for the natural gas network, which is based on *Investeringsplan* [20] and *Kwaliteits- en capaciteitsdocument* [21]. In this section we emphasize components of the network. Next, we state the risk process for the supply of natural gas and we give an overview of risks quantified by their effectiveness. Afterwards, the main cluster risks, strategic risks and capacity bottlenecks for natural gas is discussed. We end this section by illustrating a table which provides an overview of potential issues for the supply of natural gas. The second section is about the paper *Investigating the natural gas supply security* [22], which provides more information for different countries, including the Netherlands, for the security of natural gas supply. Afterwards, we present in the next section the paper *A model for investigation of optimal hydrogen pathway, and evaluation of environmental impacts of hydrogen supply system* [23]. This study is of great interest for the master project, since it presents a hydrogen supply system, similar to the one discussed in Chapter 3. The chapter is completed by trying to give answers to the research questions from Chapter 3, which are first adapted to the natural gas instance.

4.1 Setting of Stedin

The natural gas supply system and its accompanying sub-system, which we refer to as system components, are discussed in this section. We go through the risk process for the supply of natural gas. Afterwards, an overview is given of the risks quantified by their effectiveness. Then, several risks and bottlenecks are described. We continue with a table that summarizes some of the potential problems for the supply of natural gas. The section is completed by answering the research questions from Section 3.1 if hydrogen would be replaced with natural gas.

4.1.1 Smart gas network

The natural gas network is a network that transports natural gas through several components such as the pipelines system to the buildings, e.g. houses, offices, petrol stations etc. Figure 4.1 shows a natural gas network referred to as *het slimme gasnet* (English: the smart gas network) by Stedin. The network starts with transporting natural gas from the rural network to the city. Then the natural gas flows through the first circuit: the Gas receiving station (component 6 in the figure). Afterwards, the natural gas flows through the second circuit. The latter circuit consists of many components which are detailed in Figure 4.1. Since the figure is in Dutch we translate each component (including the component from the first circuit), in Appendix B.

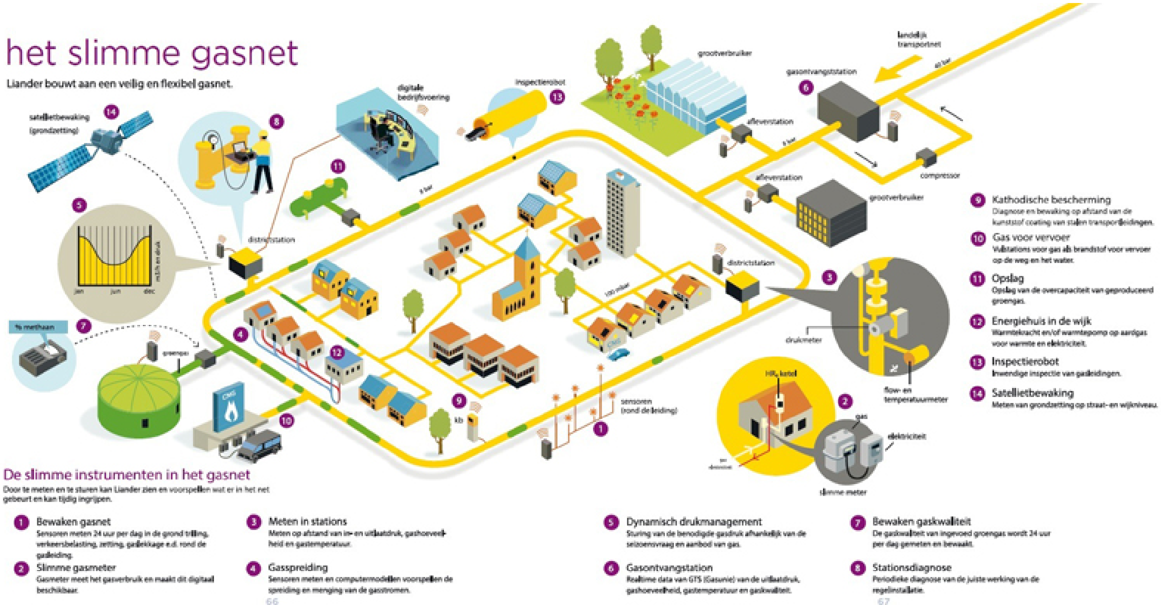

Figure 4.1: Smart gas network [24].

4.1.2 Risk process of security supply for natural gas

Stedin's risk management system distinguishes between bottlenecks and risk clusters. A bottleneck typically concerns an individual asset or specific event that may adversely affect the basis for the risk analysis regarding the supply in (electricity and) natural gas grid. The bottlenecks are assessed and then provided with a risk rating. At the system level bottlenecks are aggregated into risk clusters. These are risks that arise from the condition of a specific group with similar assets, risks with a similar cause, or a combination of both. Risk clusters therefore have a broader scope than bottlenecks.

The risk process begins when employees or stakeholders notice bottlenecks in the natural gas networks. These bottlenecks (or eventually a risk) are registered, after which they are assessed based on the company values. These company values form a basis for the risk analysis regarding the supply in (electricity and) natural gas grids [21]. The company values are listed below.

1. **Safety**

   The degree to which risks for own employees, the environment and third parties as a result of the presence of infrastructure and works on it should be minimized;

2. **Quality**

   The degree to which the quality and availability of the products and services provided by the stakeholders are met should be maximized;

3. **Financial performance**

   The degree to which the Asset Owner's requirements for financial performance are met should be maximized;

4. **Laws and regulations**

   The extent to which operations are carried out within the limits of: the designation as network operator and metering manager, the requirements imposed by the regulator and the legislator and agreements;

5. **Customer and stakeholder experience**

   The degree to which events influence the perception of Stedin's performance. It concerns the influence of customers and stakeholders;

6. **Durability**

   The degree to which the electricity and gas supply takes sustainable energy and energy savings into account should be maximized in such a way that it also functions in a socially responsible manner.

Each company value gives insight in what could go wrong and what could be a risk in the progress of supplying natural gas. These risks are quantified on the basis of the Stedin value model, see Table C.1 from Appendix C. For example, the risk 'gas evacuation hours' is directly applied to the security of supply. The bottlenecks and risks are also valued on the basis of the Stedin value mode, which are shown in Part II from Table C.1. If a risk is assessed as unacceptable or must be mitigated in accordance with policy, Stedin investigates which mitigation measures can be taken.

Thus, when capacity bottlenecks occur in the process of security supply for natural gas, there should be taken measures. Hence, when the calculations show that a capacity bottleneck is to be expected, Stedin includes this in the bottleneck register and treats it according to the risk assessment process, just described. It depends on the outcome from the risk assessment process whether a capacity bottleneck is also classified as a capacity risk. The validation can be done by checking the pressure measurements in cold periods and/or the expected increase or decrease in natural gas demand. In this way it is determined whether capacity bottlenecks actually pose a threat to the continuity of Stedin's services.

During the realization phase of the project, Stedin monitors the progress on costs, time and quality. They closely monitor the available and required grid capacity in order to transport natural gas safely and continuously. Furthermore, they also use various scenarios to predict the required grid capacity. This is how Stedin provides sufficient natural gas capacity on time and on top of that, to prevent or resolve capacity bottlenecks in time. The process ends with evaluating and monitoring the effect of the measures that are taken. But before this process can be realized, a capacity requirement estimation should be taken into account. The development of natural gas demand and supply is determined by the current market developments and customer requests. In order to identify the capacity bottlenecks in the first place, a step-by-step process [20] is given below.

1. Collecting the measured taxes per gas receiving station in previous years.
2. Collecting the meteorological information of the past years.
3. Validate and possibly adjust the grid calculation model on the basis of measured loads at the determined minimum 24-hour temperature.
4. Add the forecast for housing construction, the economic activity of small and medium-sized enterprises (SMEs) and large-scale consumption for the next 10 years for each sub-area.
5. Assessing the impact of the above developments on the capacity of Stedin's gas network through network calculations with the Irene Pro model *.

4.1.2.1 Risks to security of supply for natural gas

In this section we describe the main risks that affect the supply of natural gas. A distinction is made between two types of risks: *cluster risks* and *strategic risks*. Cluster risks are all known risks that are directly related to our scope, whereas strategic risks include organizational and long-term risks. Therefore we will only mention the main six strategic risks without going into greater depth. We end this section with capacity bottlenecks of natural gas.

4.1.2.1.1 Cluster risks Five main cluster risks for natural gas are described.

Condition of primary gas connections and condition of low pressure distribution pipes (brittle materials) combination with sinking ground The soil in Stedin's catchment area consists of soil types that continue to sink due to loading and drainage. High speed of bagging causes stress on the mainlines and house connections. This can lead to sudden complete breakdown of the pipes, leading

*A model that designs, calculates or analyzes the natural gas networks.

to gas outflow. Too much stress on the house connection can cause the house connection to crack. This will lead to an outflow of gas into the houses.

Excavation damage gas Excavation work can cause gas leaks from the main pipelines and connection pipelines. The security risk is determined by the location of the leak and the amount of gas outflow. The low pressure distribution pipelines are located just in front of the facade and the connection pipelines extend into crawl spaces. Gas can build up more easily here, which could lead to an explosion.

Influence of external infrastructure on gas pipelines Many risks in the gas network have an external cause, e.g. hydrochloric acid gas as a result of cable fire and malfunctions at underground assets such as water pipelines or district heating pipelines. To manage the risks of hydrochloric acid gas and residential fires better, an improvement program is implemented. The level of the risk is mainly determined by a small number of isolated incidents.

Water in gas pipelines A leak in a low-pressure main pipeline or connection pipeline can cause water ingress. This can happen for example due to water crossings or high groundwater levels. As a consequence a problem exists with pressure fluctuations and this can lead to interruption of the natural gas supply. Locating and repairing this type of malfunction takes a lot of time, which means that the natural gas supply is interrupted for a longer period of time.

Meter arrangement Gas outages can occur in the meter setup, e.g. too low pressure, no gas or the odorant that is mixed with the gas is smelled. This leads to an interruption of the gas supply for a number of hours in the homes.

4.1.2.1.2 Strategic risks Strategic risks encompass organization and long-term hazards, whereas cluster risks are recognized risks that are directly tied to our scope. We will simply outline six major strategic risks for natural gas without going into depth since this type of risk is outside the scope of this project.

1. Cyber security;
2. Missing developments;
3. Stranded assets;
4. Inadequately prepared for a replacement wave of obsolete assets;
5. Uncertainty surrounding the transition to sustainable gasses;
6. Losses of communication network.

4.1.2.1.3 Gas capacity bottlenecks Two main gas capacity bottlenecks are described.

Goeree-Overflakkee The gas network in the eastern part of Goeree-Overflakkee has reached its maximum capacity. An expected expansion of a large-scale consumer causes a capacity bottleneck. In order to increase the capacity of the network, it was decided to use dynamic pressure control. The pressure in the 8 bar network can be increased to a maximum of 9.5 bar if a too low pressure is measured in the periphery.

Noordoost Friesland - Dokkum/Hallum The current grid calculations of Dokkum/ Hallum show that there is not enough capacity to meet the natural gas demand at -12 degrees Celsius due to the lack of energy sources. Pressure measurements on Schiermonnikoog and elsewhere in the gas network, however, show a different picture: those measurements are considerably higher than the pressure that has been calculated. This matter is currently under research.

4.1.2.1.4 Table: Overview of the possible issues We end this section with a table that summarizes some of the potential problems for the supply of natural gas. For each problem in the table the corresponding accepted threshold and the rate/number of occurrences per year is provided when possible. These potential problems are complex risk clusters that need extra analysis to be included in the security of hydrogen supply. On the other hand, some are independent on the gas that goes through the pipelines, such as water in the pipelines. Furthermore, earlier we mentioned that Stedin plans to be extra careful with the excavation and actually to monitor the works. Therefore there will be some dependencies, but actually decreasing the risk.

Risk	Accepted threshold	Rate/N.o occurrences per year
Bad condition of primary gas connections and condition of low pressure distribution pipes combination with sinking ground	Almost injury	27.450 pieces of primary gas connections and 121 km of brittle pipes are replaced in 2019
Excavation damage gas	Almost injury and social damage of $<$ 10.000 euro	Monthly, occurs at least once in a month in Stedin
Influence of external infrastructure on gas pipelines	Almost injury, social damage of $<$ 10.000 euro, and handling of uncontrollable event within Stedin	Monthly, occurs at least once in a month in Stedin
Water in gas pipelines	Social damage of $<$ 10.000 euro	Monthly, occurs at least once in a month in Stedin
Gas outages occur in the meter setup	Almost injury	Monthly, occurs at least once in a month in Stedin
Capacity bottleneck in the gas network in the eastern part of Goeree-Overflakkee	Minimum pressure of 3.5 bar in the gas pipeline network	Happens once in 10 years in Stedin

Table 4.1: Overview of the possible issues. Sources: table C.1 and Investeringsplan 2020-2020 [20].

4.2 A model for investigation of optimal hydrogen pathway

This section is based on the literature: A model for investigation of optimal hydrogen pathway, and evaluation of environmental impacts of hydrogen supply system, by Meysam Qadrdan et al. [23]. The study presented in this paper is of great interest for the master project, since it presents a hydrogen supply system that is similar to the system in Chapter 3. In addition, the study looks at the system's environmental effects as well as ways to improve hydrogen supply.

The large-scale use of fossil fuels as a major energy source has resulted in a severe energy crisis and negative environmental consequences on a national and international scale [25]. Hydrogen is widely available: combining with oxygen to form water and combining with carbon and other elements to form fossil fuels and numberless hydrocarbon compounds. Hydrogen makes up about 0.9 percent of the earth's surface weight, making it the ninth most abundant element [26]. This is why hydrogen is frequently cited as a possible cause of nearly limitless renewable power. Although it is commonly known that utilizing hydrogen as a fuel solves many aspects of the energy-environmental issue, there are a few obstacles to overcome in constructing a hydrogen supply system and establishing broad hydrogen infrastructures. First of all, there are various effective elements (such as resource availability, existing infrastructure (road, rail, and pipeline), regional geographical characteristics, environmental implications, and cost) that may be used to determine the best hydrogen approach. The question that would arise is: what is the optimal approach for hydrogen supply in various case studies? Secondly, the environmental effects of a hydrogen energy system should be thoroughly researched. For example, certain hydrogen generation systems, such as the natural gas reformer and coal gasifier, are perhaps the most promising, produce significant amounts of carbon dioxide and other pollutants.

The Hydrogen Flow Model (HFM) is a dynamic linear programming model of a hydrogen supply system that is both a techno-economic optimization and a dynamic linear programming model. HFM reflects the flow of energy from resources to the end user in the economic and social sectors by minimizing the entire discounted costs of an energy supply system (which includes Capital, Operation, Maintenance, Resource, and even Pollution Externality) over a certain period. Hydrogen may be created from a variety of feed-stocks in this model, and commercial methods are also explored. Furthermore, there are a variety of methods for transferring hydrogen, but the best one depends on several number of factors, including the distance between the demand center and the production site, the amount of hydrogen transferred, and existing infrastructure, such as natural gas pipelines, roads, and rail. Hydrogen is dispensed to hydrogen cars at fuelling facilities. The need for hydrogen is met by allocating percentages of total power demand in the residential and commercial sectors, as well as gasoline consumption in the transportation sector, to a hydrogen supply system.

The analysis of the article reveals that large-scale hydrogen production is not prioritized in the model, owing to the high expense of a hydrogen pipeline to deliver generated hydrogen to demand areas. Internalizing the emission cost leads to minor modifications in the outcomes, such as a higher biomass use rate. The majority of hydrogen generated by a biomass gasifier is utilized in the transportation sector. Furthermore, an onsite reformer supplies the majority of hydrogen required for creating power to fulfill residential and commercial demands.

4.3 Investigating the natural gas supply security

This section is based on the literature of: Investigating the natural gas supply security, by Mehmet E. Biresselioglu et al. [22]. The authors of the paper believe that there is a index, known as the supply security index, that has the potential to serve as an effective decision-making tool for 23 nations, including the Netherlands, to improve natural gas security.

Natural gas is the third most widely used fuel, after oil and coal, accounting for 23.7 percent of worldwide energy consumption [27]. Natural gas's part of the global energy mix is growing because it is heavily concentrated, flexible, and diverse, allowing it to be utilized not just for power production but also for industrial, commercial, and residential purposes. The article's main goal is to assess and estimate the natural gas supply security of the world's top natural gas importers in terms of supply risk and market risk elements.

The PCA (Principal Component Analysis) approach was utilized to compute the natural gas supply security index in this study. PCA is a well-known and widely utilized multivariate statistical approach in a variety of fields [30]. The method's goal is to minimize the dimension of the variables in the dataset so that correlated variables may be transformed into uncorrelated variables known as components. PCA on the index score captures the interactions of the variables in the absence of an observable dependent variable.

Establishing a natural gas supplier security index across nations has several challenges. The amount of imported gas, the number of natural gas providers, the dependence on the largest supplier, import dependency, supplier fragility, and the percentage of natural gas in primary energy use are the six basic parameters used to assess susceptibility. Overall, the findings show a strong link between diversity and natural gas supply security. Diversification, in keeping with the common sense guideline of 'not placing all your eggs in one basket', has a higher influence on supply security policy making than any other topic. Choosing suppliers with lower state fragility ratings also adds to the natural gas supply security of consuming nations, despite our findings indicating that diversity is the major instrument in this context. This study adds to the very limited literature on natural gas supply security for consumption nations. It presents important statistical evidence while demonstrating an empirical evaluation of the relationships between elements and developing a discussion based on the unique natural gas supply security index. The authors of the paper believe that this index has the potential to serve as an effective decision-making tool that will improve natural gas security not just at the country level, but also at the regional and global levels.

4.4 Answers to the research questions for natural gas

In this section we adapt the research questions from Section 3.1 for the natural gas instance. Subsequently, we attempt to give answers to these question by utilizing different sources.

1. How likely is it that there is not enough natural gas in the buildings of Stad aan 't Haringvliet, in probability?

Using average data from 2013 to 2017 from the website of Netbeheer Nederland [28], we conclude that this probability equals 0.007.

2. Consider the event of not having enough natural gas in the buildings of Stad aan 't Haringvliet. How long do you expect this to last, in minutes?

From an annual report from Stedin from 2020 [29] we find the following information. Stedin aims to improve supply (e.g., natural gas) security by taking initiatives aimed at reducing downtime and at preventing interruptions. According to its 2020 annual report, the average duration of interruption in gas supply in 2018 was 122 minutes and in 2020 it was 75 minutes. Another source, Netbeheer Nederland [28], provides a similar answer. Using data from the Dutch regional grid for natural gas in 2018, we estimate that the total time spent without natural gas in buildings in 2018 was 135 minutes and 41 seconds. However, note that both sources were not based on a quiet village like Stad aan 't Haringvliet, but rather on South-Holland and the Netherlands, respectively.

Chapter 5

The Classical Model for Structured Expert Judgement

In this chapter we present the Classical Model for Structured Expert Judgement. In Section 5.1 the theory behind this model is explained. Next, the elicitation for consulting experts, which are included in the model, is discussed in Section 5.2. Subsequently, various scores are presented such as the calibration, information, and combined score in Sections 5.3, 5.4, and 5.5, respectively. The chapter ends with explaining the basic settings from a software called Excalibur that is used for the methodology Classical Model for Structured Expert Judgement, see Section 5.6. The theory in this chapter is based on the course 'Decision Making Under Uncertainty: Introduction to Structured Expert Judgment' on edX [31].

5.1 Introduction to the Classical Model

Roger Cooke and other scholars at TU Delft University developed the Classical Model (CM) for expert judgment in the 1980s. It was created in response to a rising demand for a mechanism for gathering expert opinions that contained the principles listed below.

- Reproducibility: The data, as well as the methods used to process it, should be subject to peer review, and the calculations should be repeatable by competent reviewers;
- Accountability: Reviewers should have access to the references of experts who participated in the study;
- Empirical Control: Empirical quality controls are used to quantitative expert assessments;
- Neutrality: Expert probabilities should be evaluated and combined in a way that encourages experts to give their real view;
- Fairness: Before the experts' opinions are graded, there should be no prejudgment of any kind.

The CM has established itself as the solution instrument for mathematical aggregation of judgments by incorporating these principles into a method that can be easily interpreted and executed in practice.

Through weighted linear pooling, the CM conducts a mathematical aggregation of probability distributions. Each experts' weights provide a gauge of their performance. In particular, during the development stages of CM, the emphasis on *Empirical Control* and *Fairness* principles resulted in a scoring method based on the combination of two scores, namely the accuracy score and the information score.

Obtaining projections for uncertain quantities is one of the Structured Expert Judgement (SEJ) declared goals. Point forecasts may appear appealing because they provide a predictable result, but quantifying the uncertainty that defines these values is crucial from a decision making standpoint. Subjective probability distributions, which incorporate information regarding uncertainty, are elicited from experts from this perspective. Since it is difficult for anyone to determine full probability distributions, experts are required to indicate certain quantiles of their probability distributions in the CM. For example, in this thesis $5\%-$, $50\%-$, and $95\%-$ quantiles are commonly chosen. The three values are then used to create a non-parametric probability distribution function.

In the model, a combination of the consulted experts' probability assessments is constructed. These combinations are weighted variables and are derived from proper scoring rules such that experts receive their maximum scores if and only if they state their true opinions. The Classical Model is implemented in Excalibur*, a freely available software for academic use. The software was originally developed at Delft University of Technology and it is now maintained by Lighttwist Software [32].

Two categories of variables, the seed variables and the variables of interest, are among the uncertain quantities whose distribution must be elicited by specialists. The variables of interest are those that we are interested in but for which there are no quantitative data or are inadequate. The seed variables refer to quantities for which the analyst has knowledge of the realization but not the experts. The performance of experts' uncertainty assessments is evaluated using the seed variables. Because a crucial assumption of the CM is that the performance attained for the seed questions is a good predictor of the performance in the questions of interest, the seed variables must be carefully chosen.

Now let $e = \{1, ..., N\}$ denote the index set of the N consulted experts. Then the global weights (also called the normalized combined scores) are constructed by

$$w(e) = C(e) \times I(e) \times \mathbb{1}_{\alpha}(C(e)),$$

*http://www.lighttwist.net/wp/excalibur

for each consulted expert. Here we denote $C(e)$ and $I(e)$ as the calibration and information score of expert e respectively and they will be discussed in the next two paragraphs. $\mathbb{1}_\alpha(C(e))$ is the indicator function which indicates if the calibration score exceeds a certain threshold α. This threshold ensures that only the experts with a calibration score higher than α will be taken into account in the construction of the decision maker. Note that these weights are not normalized, since they do not sum up to one. In order to normalize the weights we define $W = \sum_{e=1}^{N} w(e)$. Then for each expert the normalized weight becomes $\frac{w(e)}{W}$. These weights are also called the performance-based weights.

Next, the decision maker is constructed by taking the quantiles of the combined inputs of the experts. These quantiles are combined according to the calculated weights. There are three types of decision makers covered this report:

1. **Performance Weighted Decision Maker (PWDM)**
   In the construction of this decision maker the weights are based on the assessments of the experts. This is represented in the combined score, which will be discussed later. Normalizing the combined score yields into the weights for the experts: $w(e_i) = \frac{CS(e_i)}{\sum_{e_i} CS(e_i)}$, where $CS(e_i)$ represents the combined score of expert e_i.

2. **Optimised Performance Weighted Decision Maker (OPWDM)**
   In this decision maker we get a result of choosing a significance level for which the combined score is maximal for the decision maker. This means that this decision maker performs at least as good as all experts individually.

3. **Equal-Weighted Decision Maker (EWDM)**
   In the construction of this decision maker each expert gets the same weight, e.g. $w(e_i) = \frac{1}{N}$.

Decision makers can also be subjected to the same performance measure as the experts.

5.2 Elicitation

In this section we will take a closer look at the elicitation format. The Questions of Interest and Calibration Questions will be discussed.

5.2.1 Elicitation format

In the elicitation an expert is asked to give an estimate and its 90% confidence interval for a specific uncertain quantity.

Consider the following example from the elicitation protocol:

What is the gas consumption per hour in Stad aan 't Haringvliet, in cubic meter per hour, at temperature -12 °C?
-Answer: 5% : ..., 50% : ..., 95% : ...

The experts are asked to quantify their uncertainty by specifying quantiles of your subjective uncertainty:

- The 50%-quantile is that number for which you judge the chance half that the true value is above or below.
- The 5%-quantile is that number for which the chance that the true value is below 0.05 and the chance that the true value is above 0.95.
- The 95%-quantile is that number for which the chance that the true value is below 0.95, and the chance that the true value is above 0.05.

We always have 5%-quantile < 50%-quantile < 95%-quantile. More formally, a quantile is a part of a data set and determines how many values in a distribution are above or below a certain limit.

Suppose an expert responds as: 5% : 2000, 50% : 2500, 95% : 3000. Then this means that, in expert opinion, the true value is equally likely to be above or below 2500; there is a 90% chance that it lies between 2000 en 3000.

5.2.2 Question of Interest and Calibration question

Questions of Interests are the questions that will capture experts' uncertainty on the topics of interest for the expert judgement study. They will materialize the aim of the study and need to capture the diversity of topics that characterize the study. The calibration questions will be used to evaluate experts' ability to quantify uncertainty and to obtain performance-based weights. Those weights will be used to aggregate the distributions obtained from the Questions of Interest.

5.3 Calibration score

The calibration score measures if experts' assessments are statistically accurate hence sometimes it is referred to as the statistical accuracy. It captures how well an expert can predict the realization via their 90% confidence interval. Thus the calibration score is computed based on all the calibration questions. By defining a confidence interval for each calibration question, we can construct a probability mass function (pmf) P and an empirical sample distribution S can be generated by taking into the account the true answer of the calibration questions. In our study we can generate S by counting the number of times the realization falls in a certain quantile interval, divided by the number of calibration question, which is denoted by m. Since we are only considering 5, 50, and 95%- quantiles we have the quantiles $X(i)_1,\ X(i)_2,\ X(i)_3$ for $i = 1, ..., m$. If the quantiles are elicited for the m calibration questions with the value x_i, then the empirical distribution S over the inter-percentile intervals equals

$$S(r) = \frac{\#\{i|X(i)_{r-1} \leq x_i < X(i)_r\}}{m}, \text{ for } r = 1, ..., 4.$$

Note that in this notation the quantiles $X(i)_0 = L^*$ and $X(i)_4 = U^*$ are taken into account. L^* is calculated based on the minimum of the 5%- quantile assessment of the experts and the realizations. $U*$ is calculated based on the maximum of the 95%- quantile assessments of the experts and the realizations, as well as based on an overshoot.

An indication that the consulted expert performs well on the calibration question is when the true value of the uncertain quantities can be regarded as independent samples of P. We call an expert then well-calibrated. A measure that can measure the dissimilarity between S and P is needed in order to say if an expert is well-calibrated. We call this measure the relative information of S with respect to P (or Kullback-Leibler divergence of S and P):

$$I(S, P) = \sum_{i=1}^{4} S(i) \ln \frac{S(i)}{P(i)}, \tag{5.1}$$

$$\text{If } S(i) = 0, \text{ then } S(i) \ln \frac{S(i)}{P(i)} = 0,$$

where we have $P(1) = P(4) = 0.05$ and $P(2) = P(3) = 0.45$.

Suppose we have the statistical hypothesis:

H_0 : The uncertain quantities are independent and identically distributed with P.

Now the degree to which the data supports H_0 can be seen as a probability of observing the dissimilarity in an empirical distribution at least as large as the relative information of S with respect to P. We can use the chi-squared distribution in order to calculate the calibration score, because $2mI(S, P)$ has been shown to have an asymptotically chi-squared distribution. This yields that $2mI(S, P)$ becomes χ^2-distributed with $n - 1 = 3$ degrees of freedom, where n equals the number of inter-quantile intervals. Then the calibration score is computed using the formula:

$$C(e) = 1 - \chi^2_{n-1}(2mI(S(e), p)), \tag{5.2}$$

where m is the number of calibration questions and n is the number of inter-quantile ranges. The score will take values between 0 to 1. The higher the calibration score, the better. A perfect calibration score is when the expert is most statistically accurate, that is when the calibration score equals 1.

According to study the of Hanea and Nane [32], when different studies use the same number of calibration questions, the calibration scores can be compared across these studies. Before doing this, we have to equalize the power of the different hypothesis tests. Therefore, changing the power by leaving S calculated on m calibration questions and replacing $2m$ by $2m'$, where $m' < m$ represents the smallest number of calibration variables, we use all the m calibration variables, but pretend that the relative information is based on m' variables. The power of the calibration test (calibration power in Excalibur) is the ratio $\frac{m'}{m}$. From this we can deduce that when the number of the calibration questions increases, the calibration scores decrease for the same relative information score. Even though R.M. Cooke stated in [33] that the degree to which calibration scores are distinguished should be a model parameter one can optimise for, and that reducing the power may be important in situations when all experts are very poorly calibrated. For example, assume all experts except one have calibration scores of order less than or equal to 10^{-4}, spanning three or more orders of magnitude and one expert has a calibration better than the rest. Then all the weight may go to this one poorly calibrated expert. By reducing the power, several other combinations may be found optimal.

5.4 Information score

The second measure that objectively evaluates the experts' assessments is called the information score. In contrast to the calibration score which was computed from all the calibration question, the information score is computed for each calibration question. The information score indicates how informative the experts' distribution is with respect to the background measure used to construct the distribution [32]. Intuitively, it measures how informative the assessments are. For example, the larger the confidence interval is given by a certain expert, the less informative its prediction will be. In principle, the information score is measured with respect to two background measures.

- the uniform distribution $U(i)$ on $[X(i)_0, X(i)_n]$;
- log-uniform distribution $\ln(U(i))$ on $[X(i)_0, X(i)_n]$.

As a rule of thumb, the log-uniform background measure is used when the assessments span over 4 or more orders of magnitude. For this project, both the uniform and the log-uniform background measures have been used. This is because we have assessments within the same order of magnitude, but also assessments that would go from 10^{-6} to 10^{-5} to ... 10^{-2}. i.e. another order of magnitude.

5.4.1 Uniform background measure

Assume now that the background measure is the uniform distribution over the intrinsic range $[L^*, U^*]$, with $U(x) = \frac{x-L^*}{U^*-L^*}$, for $L^* < U^*$. We need to associate a density to the assessments of each consulted experts. We only have access to 3 quantiles from the experts' distribution for $X(i)$, thus it is necessary to interpolate between these quantiles in order to find a distribution that we can compare with $U(i)$. In other words, for each of the 4 inter-percentile intervals we have the following background measures:

$$\begin{aligned}
r_1 &= U(X_1(i)) - U(L^*) = \frac{X_1(i) - L^*}{U^* - L^*}, \text{ for } x \in [L^*, X_1(i)],\\
r_2 &= U(X_2(i)) - U(X_1(i)) = \frac{X_2(i) - X_1(i)}{U^* - L^*}, \text{ for } x \in (X_1(i), X_2(i)],\\
r_3 &= U(X_3(i)) - U(X_2(i)) = \frac{X_3(i) - X_2(i)}{U^* - L^*}, \text{ for } x \in (X_2(i), X_3(i)],\\
r_4 &= U(U^*) - U(X_3(i)) = \frac{U^* - X_3(i)}{U^* - L^*}, \text{ for } x \in (X_3(i), U^*].
\end{aligned}$$

Now we denote, for expert's distribution $F(\cdot)$:

$$\begin{aligned}
f_1 &= F(X_1(i)) - F(L^*) = 0.05,\\
f_2 &= F(X_2(i)) - F(X_1(i)) = 0.45,\\
f_3 &= F(X_3(i)) - F(X_2(i)) = 0.45,\\
f_4 &= F(U^*) - F(X_3(i)) = 0.05.
\end{aligned}$$

The information score is the average relative information of expert's distribution with respect to the uniform background measure. In this case, the information score for expert e_i for question j is determined by

$$\begin{aligned}
I_j(e_i) = \sum_{k=1}^{4} f_k \ln\left(\frac{f_k}{r_k}\right) &= 0.05\ln\left(\frac{0.05}{X_1(i) - L^*}\right) + 0.45\left(\ln\left(\frac{0.45}{X_2(i) - X_1(i)}\right)\right.\\
&\left. + \ln\left(\frac{0.45}{X_3(i) - X_2(i)}\right)\right) + 0.05\ln\left(\frac{0.05}{U^* - X_3(i)}\right) + \ln(U^* - L^*).
\end{aligned}$$

Thus is the information score of an expert over all the calibration questions defined as the average of the information scores

$$I(e_j) = \frac{1}{m}\sum_{j=1}^{m} I_j(e_i).$$

5.4.2 Log-uniform background measure

Assume now that the background measure is the log-uniform distribution over the intrinsic range $[L^*, U^*]$, with $G(x) = \frac{\ln(x) - \ln(L^*)}{\ln(U^*) - \ln(L^*)}$, for $L^* < U^*$. For each of the 4 inter-percentile intervals we have the following background measures:

$$
\begin{aligned}
r_1 &= G(X_1(i)) - G(L^*) = \frac{\ln(X_1(i)) - \ln(L^*)}{\ln(U^*) - \ln(L^*)}, \text{ for } x \in [L^*, X_1(i)], \\
r_2 &= G(X_2(i)) - G(X_1(i)) = \frac{\ln(X_2(i)) - \ln(X_1(i))}{\ln(U^*) - \ln(L^*)}, \text{ for } x \in (X_1(i), X_2(i)], \\
r_3 &= G(X_3(i)) - G(X_2(i)) = \frac{\ln(X_3(i)) - \ln(X_2(i))}{\ln(U^*) - \ln(L^*)}, \text{ for } x \in (X_2(i), X_3(i)], \\
r_4 &= G(U^*) - G(X_3(i)) = \frac{\ln(U^*) - \ln(X_3(i))}{\ln(U^*) - \ln(L^*)}, \text{ for } x \in (X_3(i), U^*].
\end{aligned}
$$

We denote the theoretical probability with respect to expert's distribution $G(\cdot)$ as $g = (g_1, g_2, g_3, g_4) = (0.05, 0.45, 0.45, 0.05)$. The information score is the average relative information with respect to the log-uniform background measure. In this case, the information score for expert e_i for question j is determined by

$$
\begin{aligned}
I_j(e_i) &= \sum_{k=1}^{4} g_k \ln\left(\frac{f_k}{r_k}\right) \\
&= 0.05 \ln\left(\frac{0.05}{\ln X_1(i) - \ln L^*}\right) + 0.45\left(\ln\left(\frac{0.45}{\ln X_2(i) - \ln X_1(i)}\right)\right. \\
&\left.+ \ln\left(\frac{0.45}{\ln X_3(i) - \ln X_2(i)}\right)\right) + 0.05 \ln\left(\frac{0.05}{\ln U^* - \ln X_3(i)}\right) \\
&+ \ln(\ln U^* - \ln L^*).
\end{aligned}
$$

Thus the information score of an expert over all the calibration questions is defined as the average of the information scores

$$
I(e_j) = \frac{1}{m} \sum_{j=1}^{m} I_j(e_i).
$$

5.5 Combined score

We have introduced the calibration and information score so far. An expert who is calibrated and informative should receive a higher score than an expert who is calibrated but not informative. And an expert who is calibrated but not informative should receive a higher score than an expert who is informative but not calibrated. In order to combine these scores to get one score for each expert, we introduce the combined score. The combined score is defined as the product of the calibration score and the information score:

$$
CS(e_i) = C(e_i) \mathbb{1}_{C(e_i) \geq \alpha} I(e_i). \tag{5.3}
$$

In this formula α represents the minimum value of the calibration score. Thus only experts with a calibration score equal or higher than α are taken into account in the performance-aggregation. The other experts are considered to be not statistically accurate enough. Note that the same performance score of experts can be use to evaluate the performance of the DMs.

5.6 Excalibur: basic settings

Before we discuss the analysis and the performance of the experts, it is convenient to explain some basic settings of Excalibur that is used in this research. The data that was gathered from the experts is analyzed in Excalibur.

First of all, Excalibur uses the following formula of the calibration score: $C(e) = 1 - \chi^2_{n-1}(2mI(S(e), p)\dot{P}ower)$. In order to make this formula equal to the ones in Section 5.3, we set *Power* equal to 1. Furthermore, the background measure for each question can be chosen to be either uniform or log-uniform. For this study, we used as well as the uniform as the log-uniform background measure. The choice of the background measure is based on the explanation of Section 5.4. Next, Excalibur used different names than the original theory. Since the analysis and performance of the experts will be given in terms of Excalibur's name, a list is given below. In this list the definition of each name can be found. The definition is derived from the original glossary of Excalibur [34] and from the explanation from *Mooc: Decision making under uncertainty: Introduction to structured expert judgement* [31].

Excalibur name	**Classical Model name**
Calibration score	Calibration score
Mean relative information score total	The average information score over all questions
Mean relative information score realization	The average information score over all the calibration questions
Unnormalized weight	The combined score

Chapter 6

Performance Analysis and Results

In this chapter we discuss the responses of consulted experts for this research about hydrogen supply in the buildings in Stad aan 't Haringvliet, see Section 6.1. In this research 9 experts were interviewed, where each of the experts has their own specialization in the hydrogen supply system, see Figure 3.1. We take a closer look at the elicitation of this research about Stad aan 't Haringvliet. In Section 6.2 the question of interest and calibration questions will be introduced and listed. Furthermore, the selection of the calibration questions will be discussed. Next, in Section 6.3 we discuss the performance of the experts and the constructed decision makers. Consequently, a critical note will be added to some of the choices made in the construction of the calibration questions. See Appendix D for the assessments of each expert per question. We continue this chapter with Section 6.4 by answering the questions of interest together with added insights and critical comments. In Section 6.5.2 the contrast between the results of hydrogen and natural gas are discussed, which is followed by a comparison between the failure rates of components for the hydrogen supply system. We end this chapter with Section 6.6, which outlines the most significant risks to the hydrogen supply system, as well as recommendations on how to mitigate them.

6.1 Experts

9 experts were consulted and interviewed in this research about hydrogen supply in the buildings in Stad aan 't Haringvliet. Each of the experts has their own specialization in the hydrogen supply system, see Figure 3.1. A larger set of experts with more affinity or knowledge about the subject would be preferred, but due to restricted and practical issues the current set of experts is considered satisfactory. We will present the consulted experts briefly and even though we mention their name and some other information about them, their assessments and performance will remain anonymous throughout the rest of the report.

Frank van Alphen
Frank is working at the Asset Management of Stedin and is in addition a hydrogen-

expert. From the initial part of this thesis he has been involved with constructing the system of hydrogen supply and providing any additional information that was relevant to this project.

Albert van der Molen
Together with Frank, Albert is working at the Asset Management of Stedin and is also in addition a hydrogen-expert. Albert has also been involved with constructing the system of hydrogen supply.

Michel Honselaar
Michel is Project Manager at WaterstofNet. Michel got involved in this project when finalizing the hydrogen supply system.

Sjoerd Delnooz
Sjoerd is Unitmanager at Kiwa Nederland and is an energy transport-expert. Therefore he is specialized in energy entering the city gate stations, gas distribution, gas in pipeline systems and the buildings.

Rob Stikkelman
Rob is an associate professor at the TU Delft and takes part of the Energy and Industry group. Furthermore, he is also the director of Center for Port Innovation. His research interests are developments of industrial infrastructures/clusters.

Jurriaan Peeters
Jurriaan is an assistant professor at the TU Delft in the Energy Technology section. His research interests are influence of wall roughness on turbulent scalar transport and heat transfer to turbulent fluids at super critical pressure.

Harm Vlap
Harm is a senior Technical Consultant at DNV GL - Oil and Gas. He has great bond with Stedin. Harm spent almost eighteen years with Gasunie N.V., the Dutch gas transmission network operator, focusing on all elements of natural gas quality, environmental challenges, and gas metering before joining DNV GL.

Martijn Duvoort
Martijn is the transformational leader and director of Energy Markets and Strategy at DNV.

María del Mar Pérez-Fortes
Mar is an assistant professor at the TU Delft takes part of the Energy and Industry group. Her research interests are: process system engineering, conceptual design, techno-economic analysis, Supply chain management, carbon capture and utilisation, and emerging technologies.

Remarks
Some of the experts claim not to be an expert for the investigation of Stad aan 't

Haringvliet. The reason we consulted them anyway was for several practical reasons. First, they considered their expertise close to the subject area. Secondly, it is a difficult task to approach people who are qualified as experts. Of the 13 experts suggested by my supervisors, only two responded positively an participated in the study. However, one of them also claimed that they are not an expert for this investigation during the elicitation. Note that with this saying the following impression is created: experts claiming to be experts and experts claiming not to be experts appear to be well qualified. Nevertheless, not all cases are that black and white. Many factors, such as insecurity, are not taken into account. Last, time also plays a role. For this master's thesis it is infeasible to wait for months for more experts who could also claim not to be an expert during the elicitation.

Worth addressing is that each expert consulted has their own expertise and that the performance analysis objectively evaluates the expertise of the experts. This means that the validation step ensures that expertise does play a role. It will be interesting to see how this affects the results and whether a relationship can be found between expertise and performance in quantifying uncertainty.

6.2 Elicitation

In this section we will take a closer look at the elicitation of this research about Stad aan 't Haringvliet. The Questions of Interest and the Calibration Questions will be listed. Furthermore, the selection of the Calibration Questions is discussed.

6.2.1 Elicitation format

In the elicitation an expert is asked to give a best estimate and its 90% confidence interval for a specific uncertain quantity. The elicitation protocol that was used for this study can be found in Appendix E. In the protocol a brief introduction to the subject is given and the elicitation format is explained. The elicitations were performed online, using one-to-one meetings. The experts were sent, prior the elicitation, a background document containing relevant information about the project Stad aan 't Haringvliet, see Appendix E. The experts were asked to consider the designed system, along with the assumptions presented Section 3.1.1.

6.2.2 Questions of Interest

The aim of this project is to quantify the risks to security of supply for hydrogen in the buildings of Stad aan 't Haringvliet. Therefore the Questions of Interest, which are listed below, are focusing on the overall risk to security of supply, along with the risks of the sub-components. These questions are of great interest since they correspond with the random variables whose distributions could not be quantified from data or previous studies. The calibration questions will be used to evaluate experts' ability to quantify uncertainty and to obtain performance-based weights. Those weights will be used to aggregate the distributions obtained from the Questions of Interest, which gives us distributions for the random variables in Table A.1.

Questions of Interest:

1. How likely is it that there is not enough hydrogen in the buildings, in probability?

2. Consider the event of not having enough hydrogen in the buildings. How long do you expect this to last, in minutes?

3. How likely is it that the hydrogen storage contains less than 70% of the storage capacity, in probability?

4. How likely is it that the amount of odorant added to the hydrogen is insufficient, i.e., enough for a leakage not to be detected, in probability?

5. Consider 1,000,000 leakages incidents in the storage. How many times does the sensor that measures leakage in the storage contain an error (so the sensor does not report the leakage, or the sensor does report a leakage when it does not occur)?

6. Suppose there are 1,000,000 leakages incidents in the distribution pipeline system. How many times does the sensor that measures leakage in the distribution pipeline system contain an error (so the sensor does not report the leakage, or the sensor does report a leakage and it is not the case)?

7. How likely is it that there is a hydrogen leakage in the storage, in probability?

8. How likely is it that there is a hydrogen leakage in the transmission pipeline system, in probability?

9. How likely is it that there is a hydrogen leakage in the distribution pipeline system, in probability?

The following questions concern the likelihood of the pressure value in each component in the hydrogen supply system. As discussed before, we aim to have a certain pressure value for hydrogen at each component. However, this certain pressure value does not have to be the maximum value as described in Chapter 3. One of the employees of Stedin suggests that during summer time the energy demand for heating purposes decreases, and a lower hydrogen supply is required by the households/buildings. The inhabitants are inclined to use less heating activities. The hydrogen in each component in the system will therefore have a smaller pressure than the maximum pressure described in Chapter 3. This is not problematic as long as the pressure of hydrogen in each component does not have a lower pressure than the maximum pressure in the consecutive component in the hydrogen supply system. For an extreme winter, we can assume that the energy demand for heating purposes will be high. We need more hydrogen supply for heating. In other words, we need hydrogen with high pressure, almost equal or equal to the maximum pressure value described in each component of the hydrogen supply system in Chapter 3. By asking the experts the questions of interest below along with the probabilistic statements, the expected time to solve the issues arising with pressure is also elicited.

10. How likely is it that hydrogen pressure in the transmission part will be lower than 40 bar, in probability?

11. How likely is it that the hydrogen pressure in the transmission part will be lower than 8 bar, in probability?

12. How likely is it that the hydrogen pressure at the city gate station will be lower than 8 bar, in probability?

13. How likely is it that the hydrogen pressure at the city gate station will be lower than 100 millibar, in probability?

14. How likely is it that the hydrogen pressure at street level will be lower than 100 millibar, in probability?

15. How likely is it that the hydrogen pressure at street level will be lower than 25 millibar, in probability?

16. How likely is it that the hydrogen pressure in the buildings will be lower than 25 millibar, in probability?

17. Suppose the compressor machine fails to compress the hydrogen to 80 bars. How long do you expect it will take a mechanic to fix this issue, in hours?

18. Assuming there is a detected hydrogen leakage in the storage, how long will it take a mechanic to fix the issue, in hours?

19. Assume a sensor that measures leakage in the storage contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

20. Assume there is a hydrogen pressure drop in the transmission pipeline system that can lead to a lack of supply. How long do you expect it will take a mechanic to fix this issue, in hours?

21. Assuming there is a hydrogen leakage in the transmission pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

22. Assuming there arises a problem with mixing hydrogen with the odorant, how *long do you expect it will take a mechanic to fix this issue, in hours?*

23. Assuming there is a hydrogen pressure failure at the city gate station, how long do you expect it will take a mechanic to fix this issue, in hours?

24. Assuming there is a hydrogen leakage in the distribution pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

25. Assume a sensor that measures leakage in the distribution pipeline system contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

26. Assuming that there is hydrogen pressure failure in the pipeline system at street level, how long do you expect it will take for mechanic to fix this issue, in hours?

27. Assuming there is a hydrogen pressure failure in the buildings, how long do you expect it will take for mechanic to fix this issue, in hours?

6.2.3 Calibration Questions

Experts' assessments were validated with calibration questions. These are question whose answers are known before or shortly after the elicitation to the analyst, but are not known to the experts. Experts' uncertainty assessments of the calibration questions can therefore be objectively evaluated, by using the calibration and information score, which we discuss earlier extensively. Several reports on the subject of hydrogen served as sources for the calibration questions. In these reports we searched for information that could be converted into a question with a numerical assessment. We assumed that the experts were not aware of the answers for these questions.

First, a dry-run was performed, using three experts. Their feedback was used to clarify and re-arrange the questions of interest and to adapt the calibration questions. As a result, a second set of calibration questions were used for the remaining 6 experts. Although our intentions were to use only assessments obtained after the dry-run, the low number of experts made us to also consider the valuable assessments obtained in the dry-run. It should be mentioned that having experts assessing two distinct sets of calibration questions poses methodological challenges. The work of this thesis addresses and proposes solutions for these challenges.

The data that is used for the calibration questions can be found in Appendix F. Below we discuss the 2 sets of calibration questions. In each elicitation, there were 11 calibration questions. The questions followed by the letter 'a' were used in the first set of calibration questions. The questions followed by the letter 'b' were used in the second set of calibration questions. The questions which are not followed by a letter were used in both sets. Several sources were used to construct the calibration question. In Appendix F the sources can be found together with the true values for the calibration questions.

Calibration Questions:

1a. What percentage of Europe's electricity is currently given by wind energy, according to Wind Europe?

1b. Natural gas consumption in The Netherlands was 36.6 billion cubic meters (bcm) in 2015. What was the consumption (in bcm) in 2020?

2a. According to Wind Europe, Europe installed 14.7 GW of new wind capacity in 2020. The Netherlands installed the most wind power capacity. How much was that (in GW)?

2b. Stedin aims to improve supply (e.g., natural gas) security by taking initiatives aimed at reducing downtime and at preventing interruptions. According to its 2020 annual report, the average duration of interruption in gas supply in 2018 was 122 minutes. What was the average duration of interruption in gas supply in 2020, in minutes?

3a. Global Market Outlook for solar power 2021-2025 is a report by Solar Power Europe. What is the total volume (in GW) the Dutch solar market is expected to reach by 2025?

3b. According to the same annual report of question 2, the annual average downtime in gas supply in 2018 was 69 seconds. What was the annual average downtime in gas supply, in seconds, in 2020?

4b. Stedin also reports the System Average Interruption Frequency Index (SAIFI), which is defined as the average number of unforeseen interruptions with which customers are faced on an annual basis. In 2019, this index was 0.005. What was the index in 2020?

4a. or 5b. What was the percentage of renewables from the Netherlands' total energy mix in 2020?

5a. The study by Khan, Al-Shankiti and Idriss (2021) reports a 28% *efficiency of green hydrogen production using solar energy, based on an analysis designed for a plant in Saudi Arabia, which is assumed to operate around 9 hours per day without grid support. What is the hydrogen production rate (ton per h)?*

6. A study by Casamirra, Catiglia and Lombardo (2009) investigated the safety of a hydrogen refuelling station by quantifying the occurrence frequency of certain accidental scenarios. A hydrogen power park, to be realized in California was used as the reference plant. What is the frequency of the event 'storage vessel overpressure', resulted from the analysis for the plant working during one year without a maintenance?

7. A 2008 report prepared by the 'Health and Safety Laboratory' in UK details the failure rates for underground gas storage. Data on eight European companies was collected, that owned 42 sites in total, which corresponds to 845 wells. Operating experience was estimated for these 42 sites and calculated to be 100,155 well years. According to this report, what was the rate for well failure, in salt caverns in Europe, per well year?

8. Data on Dutch natural gas industry, supplied by Gasunie, NAM, TAQA and Vermilion was used to compute failure frequencies. What was the average failure frequency for flange connections based on Dutch industry data?

9. According to the same report, how many incidents with flange leakages have been reported by Gasunie in the previous 12 years?

10. Leakage measurements for steel and ductile iron gas distribution systems (including seals and joints) suggest an increase in leakage volume of hydrogen when compared to natural gas. What is the factor by which the volume leakage rate for hydrogen is higher than that for natural gas?

11. The report mentions a calculation for the Dutch pipeline system from 2003, which considers a 17% hydrogen blend. What is the predicted gas leakage rate?

6.3 Performance Analysis

In this section, we report the performance of experts' assessments and the constructed decision makers. Consequently, we present the results and then a critical note will be added to some of the choices made in the construction of the calibration questions. See Appendix D for the assessments of each expert and two decision makers per question of interest. Since one expert did not answer a calibration question, we distinguish several cases while discussing scores of each expert for the different decision makers. In the first four cases we make the assumption that this expert did in fact answer the calibration question that was left open. In the first case his or her assessment is in the $<$ 5%- quantile interval. In the second case his of her assessment is between the 5%- and 50%- quantile interval. For the third case we have this assessment between the $>$ 50%- and 95%- quantile interval. The fourth case is about the assessment being in the $>$ 95%- quantile. In the last case, case 5, we delete the calibration question that was left open by this expert for all the experts and make the analysis without this question.

Two other experts did not answer several questions of interest. In order to still use their assessments for the different decision makers, we considered that the experts did not provide assessments for these questions. In this way we constructed the decision makers EWDM and PWDM. The construction of the decision maker OPWDM is not possible in Excalibur when leaving these questions open. In order to obtain scores for the decision maker OPWDM, we resolved this by another method. First the analysis in Excalibur was done by excluding the questions of interests which have not been answered by all experts. Then the second analysis has been executed with all the questions of interests, where the experts who have not provided answers to all the questions of interests have been removed. Then we combined the results of the first and second analysis.

As mentioned before, in this study we used two different sets of calibration questions. This means that we have to distinguish the analysis in Excalibur into two parts. In addition, we note that these sets have seven questions in common, answered by all the experts. This gives rise to the opportunity to merge all the experts together considering these seven calibration question. Since all the experts have answered all the seven calibration question, there is no need to distinguish the analysis in case 1 up to case 5.

The structure of this section is as follows. We display the scores of each expert in Table 6.1 and make some critical comments. Next, the scores of the constructed decision makers are discussed. We continue by merging the calibration question sets together by only taking the common question into account. In this merged study we make some notes about the new scores of the experts and constructed decision maker. Subsequently, the distribution of the decision makers are given for Question of Interest 1 and commented. For the remaining questions of interest, we refer to Appendix G.

6.3.1 Experts' performance

In Table 6.1 the calibration score, information score total, information score calibration questions, and combined score are given for each expert for the analysis that takes 11 or 10 calibration questions into account. Note that each assumption for the assessment for the expert that did not answered one calibration question is included in the table by Expert ID: E3a (case i), for $i = 1, 2, 3, 4$. Experts ID's that include a letter 'a' differ from the Experts ID's that include a letter 'b'. The latter one takes in the analysis 10 calibration questions into account, (i.e. the calibration question that was left open by an expert has been removed from the analysis), whereas the first one is about the analysis that includes 11 calibration questions into account.

First, we consider the calibration score. We know that the higher this score is, the more statistically accurate the expert is. As it can be seen in Table 6.1 every expert has a rather low calibration score, since the values are below 0.05. As a thumb of rule, the threshold 0.05 for the calibration score is used for experts being statistically accurate or not. The most calibrated expert is E2 (indicated with green) for both the analysis where we use 11 and 10 calibration questions. Overall, expert E2 is the most statistically accurate expert. All the other experts have a lower score with at most a magnitude of 10^{-4}.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
E1a	9.207E-007	2.011	1.37	1.27E-006
E2a	0.01088	1.833	0.6298	0.0085
E3a (case 1)	9.207E-007	1.602	1.419	1.307E-006
E3a (case 2)	1.196E-005	1.602	1.418	1.696E-005
E3a (case 3)	0.0001036	1.602	1.418	0.0001469
E3a (case 4)	1.987E-006	1.602	1.419	2.82E-006
E4a	1.09E-007	1.802	2.319	2.527E-007
E5a	4.845E-005	1.981	1.801	8.728E-005
E6a	1.157E-008	2.251	1.636	1.894E-008
E7a	5.842E-006	2.556	2.038	1.191E-005
E8a	1.987E-006	2.066	1.8	3.577E-006
E9a	1.02E-009	3.233	2.619	2.672E-009
E1b	2.501E-006	2.026	1.366	3.415E-006
E2b	0.00599	1.868	0.6411	0.003841
E3b	8.923E-006	1.61	1.43	1.276E-005
E4b	3.499E-008	1.547	2.152	7.528E-008
E5b	1.579E-005	1.973	1.804	2.848E-005
E6b	6.173E-009	1.916	1.291	7.966E-009
E7b	1.892E-006	2.261	1.837	3.477E-006
E8b	1.579E-005	2.009	1.79	2.826E-005
E9b	1.371E-008	3.06	2.455	3.365E-008

Table 6.1: Expert's performance: calibration score, information score total/calibration questions, combined score. The highest scores are indicated in green.

For informativeness, we look at the mean relative information score realisation. This score does not take the questions of interest into account. Here the top three informative experts in the table with letter 'a' are experts E9a (indicated in green), E4a, and E7a. For the 'b' part we also have E9b (indicated in green), E4b, and E7b.

In terms of both the calibration and information score we can indicate that the experts provide overconfident assessments, since their calibration scores are low and their information scores are high. The expert provided overestimated assessments. When combining these scores into the combined score, we see that for both analyses expert E2 has the highest score, which is indicated in green. Expert E2 has also the highest calibration score but the lowest information score. However as concluded in Section 5.5 the assessments of an expert who are calibrated but not informative result in higher overall scores than the assessments of an expert who is informative but not calibrated. Expert E9 has the highest information score. However, since this expert receives a very low calibration score, the combined score is also very low.

Investigating the difference between the information score of the experts with the questions of interest taken into account and without, we see that only expert E4 was less informative when the questions of interest were taken into account. This means that expert E4 is more unsure and thus less informative when predicting the still unknown outcome of the research. However, all the other experts became more informative when considering the questions of interest. This may be because they knew they were not going to be scored on those questions, so they dared to be more certain in their answers.

6.3.1.1 Empirical probability vector for Expert E3

As we saw in Table 6.1, we have 5 different scores for expert E3. Case 3 results into a combined score of $1.469E-4$, whereas the other cases result into a score with an order 10^{-5} or lower. In order to evaluate how likely cases 1 to 5 is to happen without being under the null hypothesis, we define the empirical probability vector for expert E3 in case i as $v_{\text{case } i} = (\frac{a}{m}, \frac{b}{m}, \frac{c}{m}, \frac{d}{m})$, where

m: number of calibration questions;
a: number of assessments in the $<$ 5%- quantile;
b: number of assessments between the 5%- and 50%- quantile;
c: number of assessments between the $>$ 50%- and 95%- quantile;
d: number of assessments in the $>$ 95%- quantile;

for $i = 1, 2, 3, 4, 5$. For expert's E3 assessments this yields the following 5 empirical probability vectors:

$$
\begin{aligned}
v_{\text{case 1}} &= \left(\frac{6}{11}, \frac{3}{11}, 0, \frac{2}{11}\right) \\
v_{\text{case 2}} &= \left(\frac{5}{11}, \frac{4}{11}, 0, \frac{2}{11}\right) \\
v_{\text{case 3}} &= \left(\frac{5}{11}, \frac{3}{11}, \frac{1}{11}, \frac{2}{11}\right) \\
v_{\text{case 4}} &= \left(\frac{5}{11}, \frac{3}{11}, 0, \frac{3}{11}\right) \\
v_{\text{case 5}} &= \left(\frac{1}{2}, \frac{3}{10}, 0, \frac{1}{5}\right).
\end{aligned}
$$

From these vectors we can deduce that the empirical probability vectors for cases 2 and 3 are more informative over the other vectors. This is because there is a higher chance to capture more calibration questions in the 90% confidence interval, than in the other cases. Analyzing cases 2 and 3 further, we see that in case 2 more questions are captured between the 5%- and 50%- quantile than in case 3. Furthermore, none of the questions are captured between the 50%- and 95%- quantile in case 2, whereas this is not the case in case 3. In the interest of not underestimating the answers for the captured calibration questions, it would be more convenient to consider case 3 for the study.

6.3.2 Decision makers' scores

Table 6.2 reports the scores of the DMs resulting from case 1. The results from the other cases can be found in Appendix H. There are small differences in DMs' performance as reported by these tables and therefore it is enough to consider the first case only. Finally, the analysis without the unanswered calibration question is given in Table 6.3.

Tables 6.2 and 6.3 show the performance of 3 different decision makers: Equal-Weighted Decision Maker (EWDM), Performance Weighted Decision Maker (PWDM), and Optimised (global) Performance Weighted Decision Maker (OPWDM). Each decision maker is followed by a number (and letter) 1a, 1b 2, or either 3. Decision makers with number 1a in their names are based on the experts who answered the first set of calibration questions. Decision makers with number 1a in their names are based on the experts who answered the second set of calibration questions. Decision makers with number 2 in their names correspond to the experts who answered the second set of calibration questions, excluding the two experts who did not answer all the questions of interest. Lastly, the decision makers with number 3 in their names are constructed through the experts who answered the second set of calibration questions and are based on questions which were answered by all experts.

Considering the calibration score in Table 6.2 (and Tables H.2, H.3, and H.4 in Appendix H) we see that EWDM1a (indicated in green) has the highest score,

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.09406	0.6432	0.2767	0.02603
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.01088	1.833	0.6298	0.00685
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.01088	1.601	0.6258	0.006807
OPWDM2	4.845E-005	1.606	1.194	5.783E-005
OPWDM3	0.01088	1.009	0.9613	0.01046

Table 6.2: Case 1 with decision makers EWDM, PWDM, and OPWDM. The realization is assumed to be below Expert's E3's 5%- quantile. The highest scores are indicated in green.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.0322	0.6556	0.2882	0.00951
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.00599	1.868	0.6411	0.003841
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.00599	1.401	0.5957	0.003568
OPWDM2	1.579E-005	1.293	1.18	1.863E-005
OPWDM3	0.008214	1.013	0.9452	0.007764

Table 6.3: Case 5 with decision makers EWDM, PWDM, and OPWDM. The assessments of the calibration question that expert E3 did not answer are deleted for every expert. The highest scores are indicated in green.

namely 0.09406, followed by EWDM1b with a score of 0.06362. Stretched towards Table 6.3 we see that EWDM1b (also indicated in green) has the highest calibration score. This score equals 0.06362 and is followed by EWDM1a with a score of 0.0322. Thus in case 5 we conclude that EWDM1b is the most statistically accurate over all the other decision makers.

For informativeness, we look at the mean relative information score realisation. This score does not take the questions of interest into account. Here the most informative decision makers according to all the cases (including the ones in Appendix H) is decision maker OPWDM2, with a score of 1.194 for the first four cases and 1.18 for case 5.

When combining these scores into the combined score, we see that for all the cases the decision maker EWDM1b has the highest score, which is indicated in green. Decision maker EWDM1b has also the highest calibration score in the table of case 5, see Table 6.3, but a low information score. However as concluded in Section 5.5 an expert who is calibrated but not informative has a higher performance and hence a higher weight than an expert who is informative but not calibrated. EWDM1a has the highest calibration score for the first 4 cases, but since its information score is so low, the combined score did not exceed the combined score of the decision maker EWDM1b. Decision makers OPWDM2 have a highest information score for all the cases. However, since these decision makers are statistically inaccurate, the combined score is also very low.

Investigating the difference between the information score of the decision makers with and without the questions of interest, we see that all the decision makers became more informative when considering the questions of interest.

6.3.3 Merged assessments

In this section we consider seven calibration questions, answered by all the experts. In Table 6.4, the performance of each expert and the scores of the decision makers are given. The performance of experts E5 and E8 is not based on all the questions of interests, since they did not answer all of them. OPWDM1 considers all question of interest, whereas OPWDM2 is based on the analysis where the questions of interest not answered by experts E5 and E8 were left out.

Considering the calibration score in Table 6.4 we see that expert E8 has the highest calibration score of all the experts, namely 0.02005. This makes expert E8 the most statistically accurate expert. The decision makers EWDM have the highest calibration score, namely 0.5322, on the calibration question. The most informative expert is E9 and the most informative decision maker is OPWDM2. Their scores are 3.204 and 1.277 respectively and they are indicated in green.

Next, we see that the combined score of expert E8 is higher than the scores of the other experts, namely 0.03627 and is indicated in green. The decision maker

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
E1	0.0002486	2.7878	2.259	0.0005623
E2	0.001521	2.666	1.398	0.002126
E3	2.307E-005	2.37	2.513	5.798E-005
E4	2.307E-005	2.684	2.995	6.909E-005
E5	2.307E-005	3.438	2.525	5.826E-005
E6	7.876E-006	3.083	1.667	1.313E-005
E7	2.307E-005	4.229	2.708	6.249E-005
E8	0.02005	2.505	1.809	0.03627
E9	0.0001892	4.18	3.204	0.0006064
EWDM	0.5332	1.229	0.768	0.4095
PWDM	0.1822	1.558	1.148	0.2091
OPWDM1	0.01616	1.711	1.015	0.01641
OPWDM2	0.1822	2.013	1.277	0.2326

Table 6.4: Expert's performance and decision makers' scores with 7 calibration questions taken into account and complete assessments. The highest scores are indicated in green.

that scores the best on the combined score is EWDM, with a score of 0.4095, which is overall very high. The score of this decision maker is also given in green in the table.

Examining the difference between the information score of the experts and decision makers with and without the questions of interest, we see that experts E3 and E4 were less informative when the questions of interest were taken into account. This means that these experts were more uncertain and thus less informative when predicting the still unknown outcome of the research. However, all the other experts and decision makers became more informative when considering the questions of interest. For some experts, their informativeness almost doubled.

We observe that the merged assessments yield for most decision makers higher calibration scores than the analysis when the assessments were not merged. In the merged case we have EWDM with highest calibration score 0.5332, whereas in the analysis without merging the experts the highest calibration score was 0.09406, attained by EWDM1a. Furthermore, the most informative decision makers from Section 6.3.2 had a score of 1.194, while the most informative decision maker from this section has a score of 1.277. Thus the analysis with merging the experts leads to a more informative decision maker. In addition, comparing the highest combined scores of both analysis we see that merging the experts leads to a higher combined score than without merging. Thus, it is desirable to consider further the merged assessments since the decision makers have higher combined scores.

6.3.4 Distribution of the decision makers per Question of Interest

In this section, we investigate how the different obtained DMs lead to different distributions for the variables of interest. We consider two graphs, which are about Question of Interest 1:

How likely is it that there is not enough hydrogen in the buildings, in probability?

The graphs regarding Question of Interest 2 up to 27 are given in Appendix G. As we see in Figure 6.1 and 6.2, the two graphs are different. Figure 6.1 shows us a graph with 100 quantile points that are interpolated from the 5, 50, and 95%- quantile. The graph shows us the distribution of the DMs when data is not merged. The 5, 50, and 95%- quantiles are also considered in Figure 6.2 together with their interpolation. The graph in Figure 6.2 presents the distribution when data is merged. While Figure 6.1 considers OPWDM in the analysis, this is not the situation when the data is merged. Due to restricted and practical issues this decision maker has not been implemented in R, resulting in omitting it in Figure 6.2.

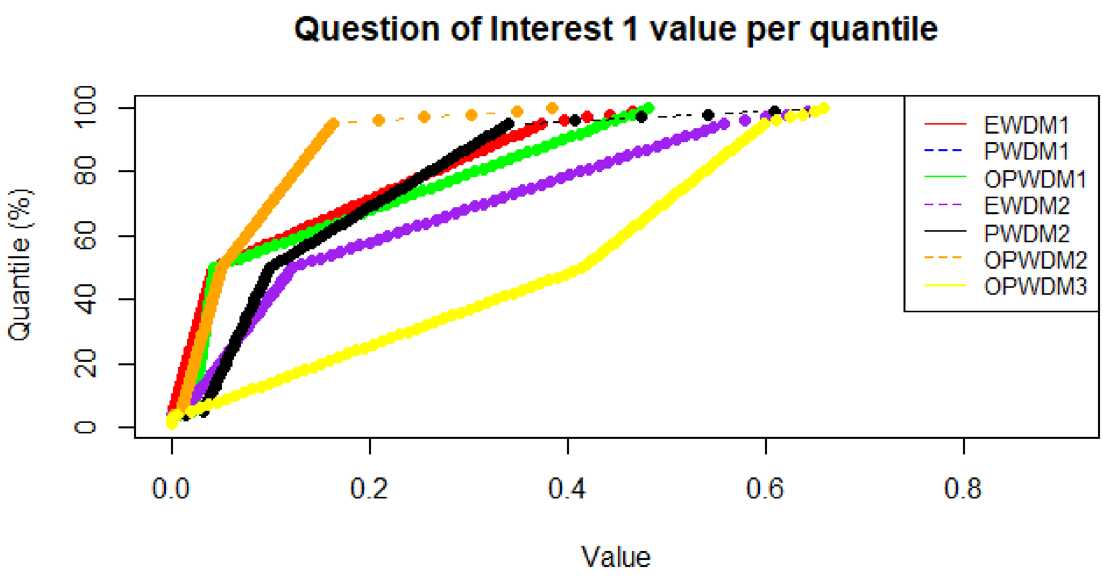

Figure 6.1: Distributions of the decision makers for Question of Interest 1. Dms results from case 1 of the analysis that considers 11 calibration questions.

Before analyzing Figure 6.1, it is convenient to give a description of the legend.

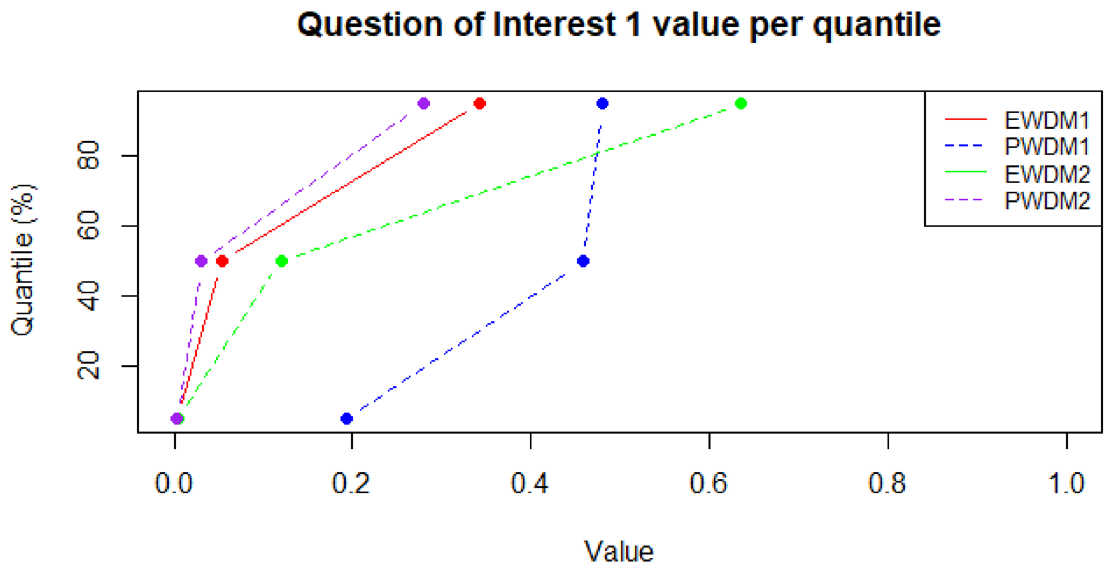

Figure 6.2: Distributions of the decision makers for Question of Interest 1. Analysis that takes calibration questions with complete assessments into account.

Desicion maker	**Description**
EWDM1	Equal-Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
EWDM2	Equal-Weighted Decision Maker with 6 experts that answered the second set of the calibration questions.
PWDM1	Performance Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
PWDM2	Performance Weighted Decision Maker with 6 experts that answered the second set of the calibration questions.
OPWDM1	Optimised Performance Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
OPWDM2	Optimised Performance Weighted Decision Maker with 4 experts that answered the second set of the calibration questions and all of the questions of interest.
OPWDM3	Optimised Performance Weighted Decision Maker with 6 experts that answered the second set of the calibration questions without the questions of interest that was not answered by everyone.

We note that for cases 2, 3, 4, and 5 led to very small differences in the distribution, and were therefore left out from this thesis. Figure 6.1 shows that OPWDM3 has a distinct distribution than the other DMs. This decision maker has constantly the largest value after the 7%- quantile, until its endpoint. Than the decision maker equals to the decision makers EWDM2 and PWDM2, namely: 0.659. Thus according to these decision makers, there is a high chance that the probability will not exceed the value 0.659.

EWDM2 and PWDM2 are very close to each other on the $0-50\%$- quantile interval. Their difference starts to increase after the 50%- quantile until 95%- quantile. Then their difference starts to decrease until they equal each other (together with OPWDM3) on the 100%- quantile.

Next, there are very small differences between OPWDM1, OPWDM3, EWDM1, and PWDM1. In fact, OPWDM1 and PWDM1 coincide. The variability between these estimates ranges from less than 0.1 to 0.4. There is even more variability in the upper bound, ranging from 0.15 to more than 0.5. According to OPWDM1, EWDM1, and PWDM1, the probability that there is not enough hydrogen in the buildings will not exceed the value 0.4817. This probability is lower according to OPWDM3, namely 0.384.

Before we continue with Figure 6.2, a description of the legend of the graph is given below.

Desicion maker	**Description**
EWDM1	Equal-Weighted Decision Maker with 9 experts but without the questions of interest that have not been answered by an expert.
EWDM2	Equal-Weighted Decision Maker with all the questions of interest taken into account but without the experts that did not answer some of the question of interest.
PWDM1	Performance Weighted Decision Maker with 9 experts but without the questions of interest that have not been answered by an expert.
PWDM2	Performance Weighted Decision Maker with all the questions of interest taken into account but without the experts that did not answer some of the question of interest.

As we see in Figure 6.2 EWDM1, EWDM2, and PWDM2 are close to each other between the $5-50\%$- quantile interval. However, PWDM1 attains bigger values in the first part of the distribution. In the $50-95\%$- quantile, EWDM1 and PWDM2 are still very close to each other, with EWDM1 having sightly higher values constantly. EWDM2 starts to grow very fast compared to the other decision makers and ends up having a larger value than PWDM2 on 95%- quantile. The values that these decision makers attain at the 95%- quantile are: 0.3424, 0.6354, 0.4793, and 0.2794 for EWDM1, EWDM2, PWDM1, and PWDM2 respectively. According to the DMs it is very unlikely that the probability of not having hydrogen exceeds these values.

6.4 Results: answering questions of interest

In the previous section, we saw that considering the calibration questions answered by all experts will lead to better scores. Thus in order to answer the questions of interest, we will use EWDM, since this decision maker has the highest combined score. We also consider the expert with the highest combined score, namely expert E8 and the decision maker PWDM for more insight. However, expert E8 did not answer all questions of interest. For these questions of interests we consider the expert with the second highest combined score, namely expert E2. Their answers are given for the 5, 50, 95%- quantile in the tables and are denoted by q_5, q_{50}, q_{95} respectively. Some rationales of the other experts will also be reported in order to motivate the estimations. For the distribution of the questions of interest that we will use in the next chapter, we use the distribution of EWDM. The question of interest are given in Section 6.2.2 and repeated here. The assessments of all the experts and decision makers' individual assessments for both the calibration questions and the questions of interest can be found in Appendix D.

Question of Interest 1: How likely is it that there is not enough hydrogen in the buildings, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	0.05	0.1	0.15
EWDM	0.003761	0.06839	0.5373
PWDM	0.02552	0.09799	0.2718

Table 6.5: The assessments of the two decision makers and expert E8 for Question of Interest 1

Thus the best estimate for how likely it is that there is not enough hydrogen in the buildings equals 0.06839, with 90% confidence interval [0.003761,0.5373], according to EWDM. Expert E8 and PWDM estimate higher probabilities. The expert considers the weather an important factor. If there is an extreme winter, then it is quite likely not to have enough hydrogen available, resulting in a high probability. For this question, the expert considered the average of the last 10 winter years.

Question of Interest 2: Consider the event of not having enough hydrogen in the buildings. How long do you expect this to last, in minutes?

Thus considering the event of not having enough hydrogen in the buildings, the best estimate for how long this last in minutes is 114 minutes, with 90% confidence interval [0.1001,5.55310]. Expert E8 and decision maker PWDM both estimate that it will last more.

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	2880	1.008E005	1440
EWDM	0.1001	114	55310
PWDM	0.1038	9386	15520

Table 6.6: The assessments of the two decision makers and expert E8 for Question of Interest 2

Question of Interest 3: How likely is it that the hydrogen storage contains less than 70% of the storage capacity, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	0.4	0.65	0.8
EWDM	0.000498	0.3328	0.7956
PWDM	0.01282	0.6253	0.7989

Table 6.7: The assessments of the two decision makers and expert E8 for Question of Interest 3

Thus the probability that the hydrogen storage contains less than 70% of the storage capacity equals 0.3328, with 90% confidence interval [0.000498,0.7956]. Expert E8 and PWDM both agree that this probability is higher, namely 0.65 and 0.6253, respectively. The expert argued as follows: in the 3 months of winters each year, the supply of hydrogen depends a lot on the buffer capacity. Given the average winter ('mild winter') he/she expects that 2 out of the 3 months there is less than 70% hydrogen capacity in the storage.

Question of Interest 4: How likely is it that the amount of odorant added to the hydrogen is insufficient, i.e., enough for a leakage not to be detected, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	0.05	0.1	0.15
EWDM	0.0004197	0.02672	0.1354
PWDM	0.002915	0.09492	0.1495

Table 6.8: The assessments of the two decision makers and expert E8 for Question of Interest 4

Thus the probability that the amount of odorant added to the hydrogen is insufficient, i.e., enough for a leakage not to be detected equals 0.02672, with 90% confidence interval [0.0004197,0.1354]. Expert E8 and PWDM both overestimate this probability, namely 0.1 and 0.09492, respectively. The expert considers the answer to be size-dependent, i.e. if the system is large, then the chance of something going wrong is bigger. Thus the more hydrogen is needed, the more odorant in the hydrogen is needed. Therefore the more likely there will be a problem with the odorant. However, these estimates are estimated to be negligible. For example, expert E4 assumes that this event will never occur, because it never happens for natural gas.

Question of Interest 5: *Consider 1,000,000 leakage incidents in the storage. How many times does the sensor that measures leakage in the storage contain an error (so the sensor does not report the leakage, or the sensor does report a leakage when it does not occur)?*

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	10000	1.0E005	2.0E005
EWDM	0.01076	36.12	150000
PWDM	4.916	92010	199100

Table 6.9: The assessments of the two decision makers and expert E8 for Question of Interest 5

Assuming 1,000,000 leakage incidents in the storage occur, the sensor that measures leakage in the storage is estimated by EWDM to contain an error 36 times of the 1,000,000 leakage incidents, with 90% confidence interval of [0,150000] errors. According to expert E8 and PWDM this happens more often, namely 100,000 and 92,010, respectively. According to expert E3 the sensors are calibrated every month. This makes the estimation of the EWDM plausible.

Question of Interest 6: *Suppose there are 1,000,000 leakage incidents in the distribution pipeline system. How many times does the sensor that measures leakage in the distribution pipeline system contain an error (so the sensor does not report the leakage, or the sensor does report a leakage and it is not the case)?*

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	10000	1.0E005	2.0E005
EWDM	0.01081	268.9	150700
PWDM	5.847	92010	199100

Table 6.10: The assessments of the two decision makers and expert E8 for Question of Interest 6

Assuming that 1,000,000 leakage incidents in the distribution pipeline system occur, the sensor that measures leakage in the distribution pipeline system is estimated by EWDM to contain an error 269 times of the 1,000,000 leakage incidents, with 90% confidence interval of [0,150700] errors. Again, according to expert E8 and PWDM this expected to happen more often, namely 100,000 and 92,010, respectively. A similar comment as for question 5 was made by Expert 3.

Question of Interest 7: How likely is it that there is a hydrogen leakage in the storage, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	1.0E-007	1.0E-006	1.0E-005
EWDM	1.584E-007	0.003276	0.07245
PWDM	1.025E-007	1.889E-006	0.02138

Table 6.11: The assessments of the two decision makers and expert E8 for Question of Interest 7

Thus the probability that there is a hydrogen leakage in the storage, according to EWDM, is expected to be 0.003276, with 90% confidence interval [1.584E-007, 0.07245]. Expert E8 and PWDM are underestimating this probability. The assessment of the expert is based on an estimation of 10% increase of leakage probability for hydrogen than for natural gas. E3 has high confidence in the storage department and believes that it is very unlikely that issues like leakage could occur. This is in line with the estimations of EWDM.

Question of Interest 8: How likely is it that there is a hydrogen leakage in the transmission pipeline system, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	0.0001	0.001	0.01
EWDM	1.266E-005	0.003971	0.06053
PWDM	3.362E-005	0.001604	0.04247

Table 6.12: The assessments of the two decision makers and expert E8 for Question of Interest 8

The probability of the event hydrogen leakage in the transmission pipeline system, according to EWDM, is expected to be 0.003971, with 90% confidence interval [1.266E-005, 0.06053]. Expert E8 and PWDM are underestimating this probability. The assessment of the expert is based on an estimation of 10% increase of leakage probability for hydrogen than for natural gas.

Question of Interest 9: How likely is it that there is a hydrogen leakage in the distribution pipeline system, in probability?

The probability of the event hydrogen leakage in the distribution pipeline system, according to EWDM, is expected to be 0.01132, with 90% confidence interval [1.235E-005,0.5432]. Expert E8 and PWDM are underestimating this probability by a factor of 10. The assessment of the expert is based on an estimation of 10% increase of leakage probability for hydrogen than for natural gas. According to

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	0.0001	0.001	0.01
EWDM	1.235E-005	0.01132	0.5432
PWDM	2.296E-006	0.0009787	0.1052

Table 6.13: The assessments of the two decision makers and expert E8 for Question of Interest 9

E3 the highest probability of failure from the hydrogen supply system is foreseen in the transmission part, due to digging. This is not in line with the estimations of EWDM. The decision makers predict a higher probability for leakage in the distribution pipeline system than in the transmission part. This assessment might be influenced by experts E5 and E6, who expect no problems at the transmission part, due to maintenance and periodic reviews. Likewise, expert E4 also did not agree with E2. Expert E4 assumes no difference between the transmission and distribution parts of the system in terms of frequency of issues that can occur. The expert does consider failures due to excavation to play a significant role.

Question of Interest 10: How likely is it that hydrogen pressure in the transmission part will be lower than 40 bar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	0.0054	0.013	0.068
EWDM	0.006145	0.1129	0.8906
PWDM	0.006914	0.09304	0.6944

Table 6.14: The assessments of the two decision makers and expert E2 for Question of Interest 10

Thus the probability of the event that hydrogen pressure in the transmission part will be lower than 40 bar, according to EWDM, is expected to be 0.1129, with 90% confidence interval [0.006145,0.8906]. This probability is slightly underestimated by PWDM and by a factor of 10 by expert E2. Questions concerning pressure drop were completely outside of experts E8's domain expertise.

Question of Interest 11: How likely is it that the hydrogen pressure in the transmission part will be lower than 8 bar, in probability?

The probability of the event that the hydrogen pressure in the transmission part will be lower than 8 bar, according to EWDM, is expected to be 0.02835, with 90% confidence interval [0.0006072,0.8489]. PWDM provides very similar best estimate, while expert E2 estimates this probability by a factor of 10. Questions concerning pressure drop were completely outside of experts E8's domain expertise. During the elicitation with E1, the expert also stated that they do not anticipate the pressure to be reduced on intentionally, and that the likelihood is

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	0.00027	0.0013	0.0054
EWDM	0.0006072	0.02835	0.8489
PWDM	0.0007255	0.02039	0.3923

Table 6.15: The assessments of the two decision makers and expert E2 in answering Question of Interest 11

thus minimal.

Question of Interest 12: How likely is it that the hydrogen pressure at the city gate station will be lower than 8 bar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	1.0E-005	0.0001	0.001
EWDM	3.478E-006	0.01499	0.1703
PWDM	1.223E-005	0.005839	0.1625

Table 6.16: The assessments of the two decision makers and expert E2 for Question of Interest 12

The probability of the event that the hydrogen pressure at the city gate station will be lower than 8 bar, according to EWDM, is expected to be 0.01499, with 90% confidence interval [3.478E-006,0.1703]. Expert E2 is underestimating this probability by a factor of 100, because the expert thinks that the city gate will not pose big issues. PWDM is also underestimating this probability. Questions concerning pressure drop were completely outside of experts E8's domain expertise.

Question of Interest 13: How likely is it that the hydrogen pressure at the city gate station will be lower than 100 millibar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	1E-018	1E-012	1E-006
EWDM	1.313E-012	0.001964	0.07481
PWDM	1.851E-013	6.3E-006	0.03367

Table 6.17: The assessments of the two decision makers and expert E2 for Question of Interest 13

The probability of the event that the hydrogen pressure at the city gate station will be lower than 100 millibar, according to EWDM, is expected to be 0.001964, with confidence interval [1.313E-012, 0.07481]. This probability is extremely underestimated by expert E2 and PWDM. Questions concerning pressure drop were completely outside of experts E8's domain expertise. A small probability for this question is also in line with the expectation of E1.

Question of Interest 14: How likely is it that the hydrogen pressure at street level will be lower than 100 millibar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	0.001	0.01	0.05
EWDM	0.0001789	0.01428	0.7172
PWDM	0.0005698	0.0935	0.7224

Table 6.18: The assessments of the two decision makers and expert E2 for Question of Interest 14

The probability of the event that the hydrogen pressure at street level will be lower than 100 millibar, according to EWDM, is expected to be 0.01428, with confidence interval [0.0001789,0.7172]. The assessment of expert E2 is close to this probability. PWDM overestimates this probability with 0.0935. Questions concerning pressure drop were completely outside of experts E8's domain expertise. Expert E5 also thinks this probability is slightly higher than the probabilities in the other part of the hydrogen supply system, due to works on the streets. According to E5, once every 3 years something is likely to go wrong.

Question of Interest 15: How likely is it that the hydrogen pressure at street level will be lower than 25 millibar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	0.001	0.01	0.05
EWDM	1.398E-006	0.00453	0.3232
PWDM	7.084E-006	0.04122	0.4744

Table 6.19: The assessments of the two decision makers and expert E2 for Question of Interest 15

The probability of the event that the hydrogen pressure at street level will be lower than 25 millibar, according to EWDM, is expected to be 0.00453, with 90% confidence interval [1.398E-006,0.3232]. Expert E2 and PWDM overestimate this probability. Questions concerning pressure drop were completely outside of experts E8's domain expertise. A small probability as an answer for this question is also in line with the expectations of E1.

Question of Interest 16: How likely is it that the hydrogen pressure in the buildings will be lower than 25 millibar, in probability?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	2.7E-006	2.7E-005	0.0027
EWDM	1.841E-006	0.003302	0.3361
PWDM	6.788E-006	0.00838	0.3613

Table 6.20: The assessments of the two decision makers and expert E2 for Question of Interest 16

The probability of the event that the hydrogen pressure in the buildings will be lower than 25 millibar, according to EWDM, is expected to be 0.003302, with 90% confidence interval [1.841E-006,0.3361]. Expert E2 underestimates this probability and PWDM overestimates it. Questions concerning pressure drop were completely outside of experts E8's domain expertise.

Question of Interest 17: Suppose the compressor machine fails to compress the hydrogen to 80 bar. How long do you expect it will take a mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E2	0.2	2	5
EWDM	0.2913	6.077	471.7
PWDM	0.2059	3.333	165.4

Table 6.21: The assessments of the two decision makers and expert E2 for Question of Interest 17

Suppose the compressor machine fails to compress the hydrogen to 80 bar. The expected time a mechanic will take to fix this issue equals 6.077 hours, with 90% confidence interval of [0.2913,471.7] hours. Expert E2 thinks it will take 2 hours and PWDM agrees with 3.333 hours. Questions concerning pressure drop were completely outside of experts E8's domain expertise.

Question of Interest 18: Assuming there is a detected hydrogen leakage in the storage, how long will it take a mechanic to fix the issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	12
EWDM	0.2548	9.898	5570
PWDM	0.2573	4.463	3606

Table 6.22: The assessments of the two decision makers and expert E8 for Question of Interest 18

Suppose there is a detected hydrogen leakage in the storage. The expected time a mechanic will take to fix this issue equals 9.898 hours, with 90% confidence interval of [0.2548,5570] hours. Expert E8 and PWDM think that it can be fixed faster, namely 4 and 4.43 hours, respectively.

Question of Interest 19: Assume a sensor that measures leakage in the storage contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	12
EWDM	0.04659	3.175	565.3
PWDM	0.1297	3.976	57.89

Table 6.23: The assessments of the two decision makers and expert E8 for Question of Interest 19

Assuming a sensor that measures leakage in the storage contains an error, the expected time a mechanic will take to fix this issue equals 3.175 hours, with 90% confidence interval of [0.04659,565.3] hours. Expert E8 and PWDM are slightly overestimating EWDM's best estimate with 4 and 3.976 hours, respectively.

Question of Interest 20: Assume there is a hydrogen pressure drop in the transmission pipeline system that can lead to a lack of supply. How long do you expect it will take a mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	1	2	3
EWDM	0.6266	7.962	110.3
PWDM	0.7557	2.081	21.83

Table 6.24: The assessments of the two decision makers and expert E8 for Question of Interest 20

Suppose there is a hydrogen pressure drop in the transmission pipeline system that lead to a lack of supply. The expected time a mechanic will take to fix this issue equals 7.962 hours, with 90% confidence interval of [0.6266,110.3] hours. Expert E8 and PWDM are underestimating EWDM's best estimate with 2 and 2.081 hours, respectively.

Question of Interest 21: Assuming there is a hydrogen leakage in the transmission pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

Assuming that there is a hydrogen leakage in the transmission pipeline system, the expected time a mechanic will take to fix this issue equals 7.351 hours, with 90% confidence interval of [0.3241,46.28] hours. Expert E8 and PWDM are underestimating EWDM's best estimate of fixing it by 4 and 4.768 hours, respectively.

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	24
EWDM	0.3241	7.351	46.28
PWDM	0.9094	4.768	28.75

Table 6.25: The assessments of the two decision makers and expert E8 for Question of Interest 21

Question of Interest 22: Assuming there arises a problem with mixing hydrogen with the odorant, how long do you expect it will take a mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	12
EWDM	0.2824	3.421	12.68
PWDM	0.6592	3.939	12.09

Table 6.26: The assessments of the two decision makers and expert E8 for Question of Interest 22

Assuming there arises a problem with mixing hydrogen with the odorant, the expected time a mechanic will take to fix this issue equals 3.421 hours, with 90% confidence interval of [0.2824,12.68] hours. The expected times according expert E8 and PWDM are close to EWDM's best estimate, namely 4 and 3.939 hours, respectively.

Question of Interest 23: Assuming there is a hydrogen pressure failure at the city gate station, how long do you expect it will take a mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	12
EWDM	0.1602	6.868	1426
PWDM	0.1106	3.945	70.84

Table 6.27: The assessments of the two decision makers and expert E8 for Question of Interest 23

Suppose there is a hydrogen pressure failure at the city gate station. The expected time a mechanic will take to fix this issue equals 6.868 hours, with 90% confidence interval of [0.1602,1426] hours. Expert E8 and PWDM are underestimating EWDM's best estimate it by 4 and 3.945 hours, respectively.

Question of Interest 24: Assuming there is a hydrogen leakage in the distribution pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	24
EWDM	0.3343	5.4	25.04
PWDM	1.289	11.73	23.97

Table 6.28: The assessments of the two decision makers and expert E8 for Question of Interest 24

Suppose there is a hydrogen leakage in the distribution pipeline system. The expected time a mechanic will take to fix this issue equals 5.4 hours, with 90% confidence interval of [0.3343,25.04] hours. Expert E8 is underestimating EWDM's best estimate with 4 hours, whereas the PWDM overestimates it with 11.73 hours.

Question of Interest 25: Assume a sensor that measures leakage in the distribution pipeline system contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	4	12
EWDM	0.02458	3.452	560.4
PWDM	0.2871	3.965	35.45

Table 6.29: The assessments of the two decision makers and expert E8 for Question of Interest 25

Suppose a sensor that measures leakage in the distribution pipeline systems contains an error. The expected time a mechanic will take to fix this issue equals 3.452 hours, with 90% confidence interval of [0.02458,560.4] hours. The expected time values of expert E8 and PWDM are close to the expected time of EWDM, namely 4 and 3.965 hours, respectively.

Question of Interest 26: Assuming that there is hydrogen pressure failure in the pipeline system at street level, how long do you expect it will take for mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	3	12	24
EWDM	0.5033	3.234	24.17
PWDM	0.9126	11.32	24.17

Table 6.30: The assessments of the two decision makers and expert E8 for Question of Interest 26

Suppose that there is hydrogen pressure failure in the pipeline system at street level. The expected time a mechanic will take to fix this issue equals 3.234 hours, with 90% confidence interval of [0.5033,24.17] hours. Expert E8 and PWDM are both overestimating EWDM's best estimate with 12 and 11.32 hours, respectively.

Question of Interest 27: Assuming there is a hydrogen pressure failure in the buildings, how long do you expect it will take for mechanic to fix this issue, in hours?

Expert and Decision maker	q_5	q_{50}	q_{95}
E8	2	4	12
EWDM	0.3559	3.987	12.79
PWDM	1.118	3.944	12.13

Table 6.31: The assessments of the two decision makers and expert E8 for Question of Interest 27

Assuming that there is a hydrogen pressure failure in the buildings, the expected time a mechanic will take to fix this issue equals 3.987 hours, with 90% confidence interval of [0.3559,12.79] hours. The expected times according expert E8 and PWDM are close to EWDM's best estimate, namely 4 and 3.944 hours, respectively.

6.5 Comparison of results

In this section, an overview of experts' and DMs' assessments is provided. Moreover, the contrasts between the results for hydrogen from the SEJ research and natural gas based on the findings of network operator Netbeheer Nederland and an annual report from Stedin are discussed. In addition, a comparison between the failure rate of components experts' individual judgments and the estimates resulting from the hydrogen supply system based on the SEJ results is provided.

6.5.1 Comparison of end results between hydrogen and natural gas

Regarding the two outcomes for the security of hydrogen supply in Stad aan 't Haringvliet for heating purposes, the best estimate from EWDM will be compared to the findings from Netbeheer Nederland's website [28].

As noted in the preceding section, the best estimate according to EWDM for how likely it is that there is not enough hydrogen in the buildings equals 0.06839 with 90% confidence interval of [0.003761, 0.5373]. Using average data from 2013 to 2017 from the website of Netbeheer Nederland [28], we conclude that this probability equals 0.007. There is a one-order difference if we use the answer from the 50%- quantile for the hydrogen case.

The disparity may be explained by the fact that the first probability is based on the SEJ research, while the second probability is based on the average number of natural gas supplies from 2013 to 2017. Furthermore, the first probability is based on Stad aan 't Haringvliet, which is regarded as a sleepy town, whereas the second probability is a depiction of the Netherlands' regional grid operators. As a result of this assertion, the hydrogen scenario should have a lower probability than the natural gas scenario. Some experts deemed the production side of hydrogen to be their largest concern, which could explain why the estimates for the hydrogen instance are larger than the natural gas instance. Another issue is that most experts overlooked the fact that Stad aan 't Haringvliet is known for being a sleepy town.

If we compare the the average probability for not having natural gas in the homes from 2013 to 2017 with the 90% confidence interval of [0.003761, 0.5373], we can draw the conclusion that this probability of 0.007 is captured in the the confidence interval. However, this interval has a broad range, which makes the comparison more challenging.

Considering the event of not having enough hydrogen in the buildings of Stad aan 't Haringvliet, EWDM's best estimate for how long this will last is 114 minutes with 90% confidence interval of [0.1001, 55310]. Using data from the Dutch regional grid for natural gas in 2018, we estimate that the total time spent without natural gas in buildings in 2018 was 135 minutes and 41 seconds. The best SEJ study estimate for hydrogen is lower than the time for natural gas in 2018 according to Netbeheer Nederland [28]. The small discrepancy can be explained by the fact that most experts assumed that the hydrogen system would function similarly to the natural gas system and therefore provide similar outcomes.

From an annual report from Stedin from 2020 [29] we find the average duration of interruption in gas supply in 2020 was 75 minutes. The discrepancy between the annual report from Stedin [29] and the SEJ report can be explained in a similar way as for the first research question.

6.5.2 Comparison of the components

The hydrogen supply system presented in Chapter 3 can be quantified using the assessments from the SEJ study. Resulting failure rates of the system components can be compared with the individual assessments of experts, and this section reports on these comparisons.

The hydrogen supply system is constructed in such a way that it considers sensors that measure leakage in the storage and the distribution component. According to the SEJ research, out of 1,000,000 leakage incidents in the storage, it is expected to have 36 sensor errors (i.e. when the sensor does not report the leakage, or the sensor wrongly reports a leakage) in the storage. However this quantity is substantially higher for the distribution component, at 269 sensor failures. As a consequence, based on the experts' combined findings, it would be a wise option to place a greater emphasis on sensors in the distribution component than in storage in order to lower amount of errors. Nonetheless, it is expected that the sensors in the hydrogen supply system are calibrated every month, based on the reasoning of expert E3. As a result, the sensors will not constitute a treat for hydrogen supply security.

When it comes to the time it takes a mechanic to repair a sensor that has a problem, the combined results of the experts reveal that a mechanic requires 3.175 hours in storage and 3.452 hours in distribution. Expert E6 believes that the position of the sensors in the system is critical since it affects how efficiently a mechanic can operate. If the position of the sensor in the components was disclosed to the experts, their assessments might have changed. Nevertheless, the detailed position of the sensors were not taken into account in this master thesis.

We investigate hydrogen leakages in three aspects of the hydrogen supply model: storage, transmission, and distribution. According to the experts' aggregated findings, the distribution system is the most vulnerable to a hydrogen leak. The chance of a leak in this part is 0.01132, whereas the chances of a leak at the storage and transmission parts are 0.003276 and 0.003971, respectively.

Expert E1 thinks that the greatest risks from the hydrogen supply system correspond to leakages. In particular, the leakages on street level. The experts motivates this by saying that the likelihood for having leakages at street level is greater than in the other parts of the hydrogen supply system due to human activities such as digging. Expert E2 is on the same page as expert E1. Expert E4 also stated that excavation is seen as posing the highest risk to the supply system. E5 assigns higher risk to this part of the supply system compared to the other parts. According to this expert, street construction an accident more likely to occur. 'Every three years, something is likely to go wrong,' said expert E5. Lastly, rationals of expert E9 concur with all of these experts.

When it comes to the amount of time it takes a mechanic to remedy a leak, the SEJ research shows that the storage gets the greatest attention. According to the estimations, a mechanic will need 9.888 hours to remedy the leak in the storage. Furthermore, the estimations suggest that leaks in the transmission and distribution parts can be eliminated in 7.351 hours and 5.400 hours, respectively.

In light of a period of high (or low) demand for hydrogen, we may deduce from the SEJ findings that the transmission component is the most challenging aspect of achieving an adequate hydrogen pressure. The probability of an inadequate hydrogen pressure in the transmission component is 0.1129 (or 0.02835). The components city gate station, distribution part, and residences are the next components in the hydrogen supply system following the transmission component. For these components the probability of the event having an insufficient hydrogen pressure decreases consecutively.

Expert E1 does not believe that a pressure decrease will occur on purpose. Expert E2 also believes that a pressure drop to a critical value (<100 millibar) at the distribution system will never occur. Their motivation stems from the fact that the system is designed to ensure that there is always enough sustainable pressurized hydrogen at each component. Expert E4, on the other hand, predicts a decline in pressure throughout the winter. Expert E7 has a different viewpoint, namely that the pressure value of hydrogen is nearly always lower than the pressure value mentioned in the project description. The pressure values given in the project description, according to the experts, are indicative of the maximum pressure value. In general, the hydrogen pressure will be lower than this maximum value due to the demand of hydrogen. As a result, expert E7 thinks that a decline in hydrogen pressure will not result in a shortage of supplies.

According to the combined results of the experts, the transmission part is not only the most challenging component for the hydrogen supply system for having a hydrogen pressure drop, but it is also the component where mechanics need more time to solve the hydrogen pressure drop. According to the SEJ research, a mechanic will require 7.962 hours to restore the hydrogen pressure to its proper level, but a mechanic working in the compressor would need 6.077 hours. The duration is projected to be substantially shorter for mechanics on the street and in the dwellings themselves, namely at 3.234 and 3.987 hours, respectively.

We wrap up this section with 3 tables that summarizes the likelihood, resulting from the experts, of the risks we have examined, risk classification of a component, and time to restore the hydrogen supply. In Figure 6.3 each risk has been assigned a low, medium, or high likelihood. These likelihood are based on the assessment of the experts. For example, almost everyone agreed that hydrogen leakage in the distributional system posed the highest risks. Therefore this risk has been assigned a high likelihood. Furthermore, each risk has a color that indicates the severity of the risk. A minor impact on the hydrogen supply system corresponds to a green colored risk. These risks influence the process of the hydrogen supply system, but not the supply of hydrogen. An example is a case when there is a malfunction in a sensor. This malfunction does not affect the supply of hydrogen but affects the system's optimal working process since there is a mechanic needed to fix the malfunction. A moderate impact on the hydrogen supply system corresponds to a yellow colored risk. This kind of risk could lead to the event that the buildings are not supplied with green hydrogen but other types of hydrogen. At last, a high impact on the hydrogen supply system corresponds to a red colored risk. These risks directly affect the supply of hydrogen to the buildings. We see from Figure 6.3 that the events of having hydrogen leakage in the distribution system and hydrogen pressure drop in the transmission system appear to be the most vulnerable parts of the system, since their likelihood is the highest among the other components and their impact on the hydrogen supply is high.

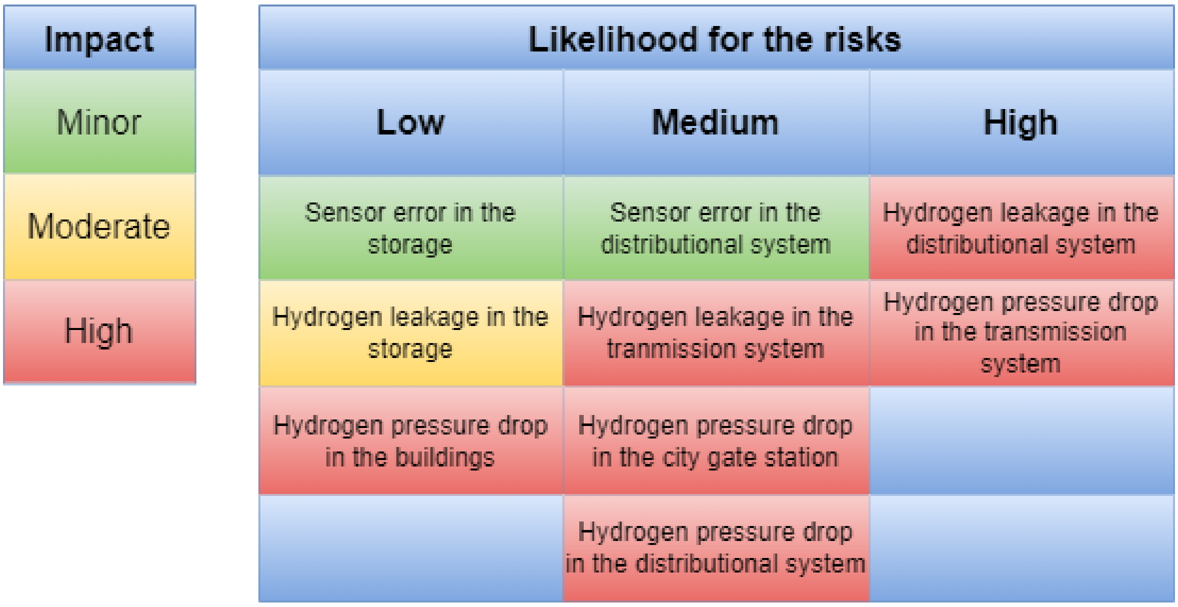

Figure 6.3: Likelihood, resulting from experts, and impact of the risks in the hydrogen supply system

In Figure 6.4 the risk classification is given according to the assessments of the experts and EWDM. The impact of a risk on the components storage, transmission pipeline system, city gate station, and distribution pipeline system is classified as minor (green), moderate (yellow), high (orange), and severely high (red). The figure shows that all experts (and thus also EWDM) classified the impact on the risks in the storage with green. This means that everyone expects nothing to happen in the storage that could disturb the hydrogen supply system. The probabilities from the elicitation regarding the risks in the storage are lower than the probabilities assigned to the risks in other components. As we mentioned beforehand, almost everyone expects that the city gate station will also not form a threat to the hydrogen supply system. Since the probabilities from the elicitation regarding the problems in the city gate station are higher than the risks in the storage, we classified the impacts as moderate. Note that in Figure 6.4 expert E8 did not provide an assessment for the city gate station and has therefore no impact assigned. The impact of the risks on the transmission pipeline system is classified as high by most experts, i.e. the probabilities from the elicitation regarding the risks on the transmissions pipeline system are higher than the probabilities about the risks regarding the city gate station but lower than the probabilities about risks for the distribution pipeline system. In general, challenges with the distribution pipeline system are expected to have the greatest impact on the hydrogen supply system, since the probabilities regarding risks in the distribution pipeline system assigned by the experts are higher than the probabilities for any other risks. We may deduce from Figure 6.4 that most experts generally agreed on the degree of the difficulties with the components in the hydrogen supply system.

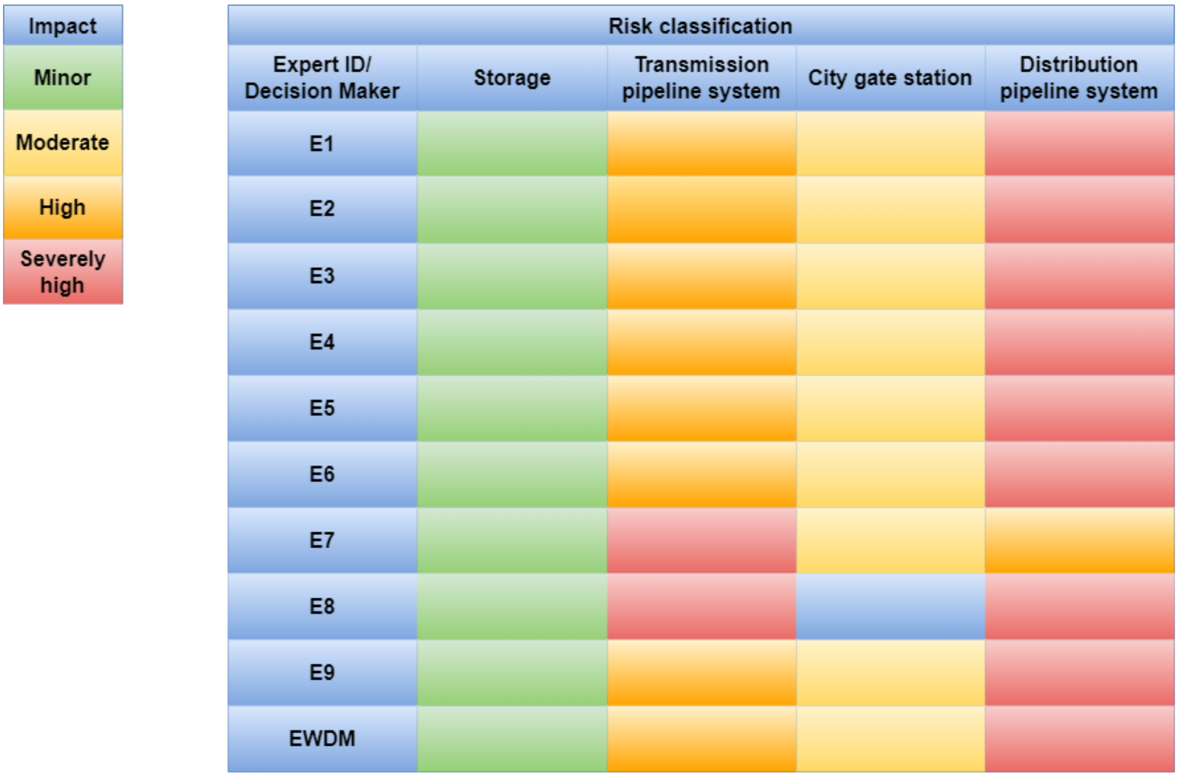

Figure 6.4: Risk classification according to the assessments of the experts.

As stated beforehand, the experts disagreed about the expected time mechanics needs to solve a problem. In Figure 6.5 we give an overview of their predictions. Whereas Figure 6.4 considers four components from the hydrogen supply system, Figure 6.5 considers five components. Therefore we classify the impact of the time to restore a problem as minor (green), moderate (yellow), high (orange), severely high (red), and extra high (black). The impacts were assigned in a similar way as in Figure 6.4. The green coloring in the figure corresponds to experts and EWDM expecting that this component needs the shortest restore time. Yellow-colored cells correspond to experts and EWDM expecting that the restore time will take longer in these components than the components with green color, but shorter than the other components. Arguing in this way, we can deduce that the components which are assigned a black cell by the expect and EWDM, are expected to have the longest restore time. Note that in this figure expert E8 did not provide an assessment for the compressor.

6.6 Mitigation of the biggest risks of component failures

In this section we discuss the biggest risks of the hydrogen supply system and how to mitigate them.

Figure 6.5: Time to restore for the supply according to the assessments of the experts.

Although it was determined that the system's sensors did not represent a significant threat to the hydrogen supply, it is still a good idea to calibrate the sensors in the storage and distribution systems on a monthly basis, as expert E3 mentioned. Experts E7 and E9 also noted the following mitigation: it will be advantageous to have a duplicate sensor available in order to reduce the working time of a mechanic.

Based on the aggregated evaluations as well as the expert's individual elicitations, it may be determined that the distribution system poses the greatest danger of hydrogen leakage. The most major concern is excavation on the street level. Sending a team of professionals from Stedin to assist in the digging process might be an excellent way to mitigate the danger of excavation failures.

The transmission system, according to SEJ study, is the most vulnerable to a hydrogen pressure drop. According to some experts, this may occur during the winter owing to a lack of hydrogen capacity at a time when demand for hydrogen is substantial. Expert E7 believes that there is a good chance that there will be not enough hydrogen in the storage in the winter. This is in accordance with E8, who believes that the hydrogen buffer is highly dependent on the capacity of it. According to this expert, there will be insufficient hydrogen buffer for 2 to 3 months, i.e. throughout the winter.

Focusing more on the production system might help mitigate the possibility of a lack of hydrogen capacity (during the winter). The hydrogen supply system in this master's thesis, on the other hand, believes that there will always be enough hydrogen. It should be mentioned that the experts were concerned with this assumption and refused to acknowledge it.

However, if we continue to think that the transmission system is the most vulnerable to a hydrogen pressure drop, we may install sensors that measure the pressure of hydrogen in this component of the hydrogen supply system as a precaution. In this way the sensors will notify immediately when a mechanic is needed. Consequently, this will result in a decrease of the solving time of the problem when the hydrogen pressure is not attained at the right value. Another mitigation could be the assumption of expert E5 and E6. These experts assume that there will be significantly more maintenance at the transmission part and as a consequence, there will occur less failures in this part of the supply system.

Expert E5 considers the production part as posing the highest problem, as it is highly dependent on the weather conditions. As mentioned before, in the hydrogen supply system it is assumed that there will always be hydrogen available for the compressor. We either acquire green hydrogen produced by wind turbines or solar panels, from the storage, or other types of hydrogen from tube trailers. Nevertheless, according to expert E7, who also foresees the production as the most critical component of the system, we must consider the hazards associated with the production part, such as the effect of snow on the tube trailers. According to this expert, the risks associated with manufacturing are far greater than the risks associated with leaks and sensor faults, for instance. A mitigation for the problems at the production system could be that Stedin would need to increase redundancy in the storage or hydrogen capacity overall.

According to the majority of experts, the city gate station and storage are seen to be the least risky of all the components in the hydrogen supply system. The city gate, according to expert E2, will not be a major concern. This is in line with E3, who emphasized that the city gate station should not cause too many complications. Because everything is nicely arranged in the storage, this expert has great faith in it. Due to personal experience, this expert believes it is extremely unlikely that complications would arise at these two components, that is, the storage and cite gate station. Expert E4 also believes that breakdowns at the city gate station and storage are unlikely.

According to most of the expert, it is estimated that the city gate and storage a considered the lowest risk factor from all the components in the hydrogen supply system. Expert E2 believes that the city gate will not pose big issues. This is in line with E3, who stated that not many problems are expected at the city gate. This expert has also high confidence in the storage because everything is well organized there. For this expert it is very unlikely that issues occur at these two components due to personal experience. Furthermore, expert E4 does not expect failures to occur at the city gate and storage too. This is based on the premise that hydrogen is processed similarly as natural gas.

We end this section with a table illustrated in Figure 6.6. This table summarizes for every risk from the hydrogen supply system one or more mitigations to improve the security of hydrogen supply in Stad aan ‘t Haringvliet.

Risk mitigation	
Risk	**Mitigation**
Sensor error in the storage	Sensors should be calibrated at least once a month, and duplicate sensors should be kept on hand.
Sensor error in the distributional system	Sensors should be calibrated at least once a month, and duplicate sensors should be kept on hand.
Hydrogen leakage in the distributional system	A team of professionals from Stedin should be deployed to assist with the excavucations.
Hydrogen pressure drop in the transmission system	Sensors should be installed in the transmission system and more maintenainces should be scheduled.
(Problems at the production of hydrogen)	(Increase redundacy in hydrogen storage or hydrogen capacity overall)

Figure 6.6: Risk from the hydrogen supply system and one or more mitigations.

Remark 1. *When we discussed the findings of the SEJ study with Stedin, one expert told us that he does not expect much digging at Stad aan 't Haringvliet since it is regarded as a sleeping town. This crucial information was left out of both the project description and the elicitation protocol. However, many of the consulted experts considered excavating to be one of the greatest risks to the hydrogen supply.*

Chapter 7

Bayesian Network

In this chapter we introduce Bayesian Networks, which have been used to model stochastically the security of supply for the project Stad aan 't Haringvliet. First, an introduction of probability theory concepts which are used by Bayesian Networks is provided, in Section 7.1. Then an introduction of this mathematical phenomenon will be given in Section 7.2. We continue this chapter by discussing different types of Bayesian Networks in Section 7.3, where some examples will be given. The chapter ends with explaining the basic features of a software called UNINET that is used for the modelling of the Bayesian Network for the uncertainty analysis, see Section 7.4.

7.1 Probability theory

In this section we introduce concepts of probability theory that are needed to understand Bayesian Networks.

Definition 1. *Two events X and Y are called independent if one of the following conditions holds:*

- $P(X|Y) = P(X)$ *and* $P(X), P(Y) \neq 0$;
- $P(X \cap Y) = P(X)P(Y)$.

Definition 2. *Two events X and Y are called conditionally independent given event Z (notation:* $P(X, Y|Z)$ *for* $P(Z) \neq 0$*) if one of the following conditions holds:*

- $P(X|Y \cap Z) = P(X|Z)$ *and* $P(X|Z), P(Y|Z) \neq 0$;
- $P(X, Y|Z) = P(X|Z)P(Y|Z)$.

The following theorem is named after its inventor T. Bayes (1702-1761), a mathematician from the United Kingdom. This theorem is useful in Bayesian Networks.

Theorem 1. *(Bayes) Given two events X and Y such that $P(X), P(Y) \neq 0$, then the conditional probability of X given Y is defined by*

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}. \tag{7.1}$$

An extension of Theorem 1 is possible and is called the general Bayes theorem, see Theorem 3. We need this extension, since it allows us to take more events into consideration. However, in order to do that we require the following theorem which is known as the Law of Total Probability.

Theorem 2. *(Law of Total Probability) Given n mutually exclusive events $A_1, ..., A_n$ such that their probabilities sum is unity and their union is the event space E, then $A_i \cap A_j = \emptyset$, for all $i, j = 1, ..., n$ such that $i \neq j$, and $\cup_{i=1}^{n} A_i = E$. Then the Law of Total Probability is given by*

$$P(B) = \sum_{i=1}^{n} P(B|A_i)P(A_i), \tag{7.2}$$

where B is an arbitrary event, and $P(B|A_i)$ is the conditional probability of B on A_i.

Theorem 3. *(General Bayes) Given events X_i and Y such that $P(X_i), P(Y) \neq 0$ for $1 \leq i \leq n \leq \infty$, then the conditional probability of X_i given Y is defined by*

$$P(X_i|Y) = \frac{P(Y|X_i)P(X_i)}{\sum_i^n P(Y|X_i)P(X_i)}. \tag{7.3}$$

The following definition explains what conditional independent random variables mean since Bayesian Networks use condition independence for probability distribution functions.

Definition 3. *Let X, Y, Z be three events. X and Y are called conditionally independent given Z if and only if:*

- *$P(Z) > 0$, and*
- *$P(X|Y, Z) = P(X|Z)$.*

This equivalence in Definition 3 emphasizes that Y has no influence on the validity of X.

We turn from probability and events to random variables and distribution in the next lemma. The importance of this change will be convenient later in this chapter, since we will use this lemma together with another theorem for new findings.

Lemma 4. *Consider X_1, $X_2, ..., X_n$ random variables. Then we can write the joint probability density for the random variables as*

$$f(x_1, ..., x_n) = f(x_1) \prod_{i=2}^{n} f(x_i|x_1, ..., x_{i-1}). \tag{7.4}$$

7.2 Introduction to Bayesian Networks

Bayesian Belief Networks (BBNs), also called Bayesian Netwoks (BNs), fall under the category of Probabilistic Graphical Modelling that is used to quantify uncertainties by using the concepts of probability theory. The networks provide a graphical representation of higher dimensional uncertainty distributions over a set of random variables. In order to give a formal definition of a Bayesian Network we need to define what a Directed Acyclic Graph is.

Definition 4. *(Directed Acyclic Graph) A graph* $G = (V, E)$ *with the set of nodes* V *and the set of arcs* E *is a Directed Acyclic Graph (DAG) if*

1. *The set of nodes,* V*, has a finite cardinality, and;*

2. *The set of arcs, E, has no directed cycle and that for all arcs* $(a, b) \in E$ *implies* $a \rightarrow b$*.*

An example of a DAG with 5 random variables is given in Figure 7.1. Here the cardinality of the set of nodes is 5, i.e. $|V| = 5$. Furthermore, there are no cycles in the graph and each arc (a, b) starting from node a to node b implies $a \rightarrow b$, for $a, b = 1, 2, 3, 4, 5$.

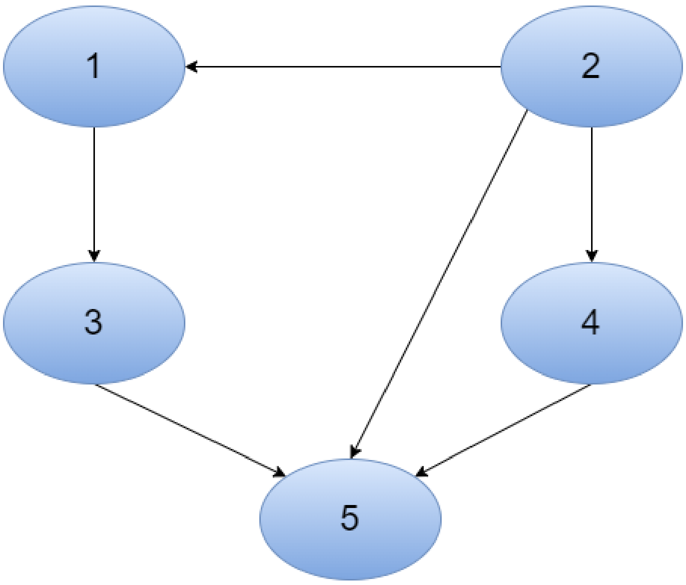

Figure 7.1: Example of a Directed Acyclic Graph (DAG).

Below, a formal definition of a Bayesian Network is given.

Definition 5. *(Bayesian Network) Bayesian Networks (BNs) are probabilistic graphical models that represent a set of random variables as nodes and their conditional (in)dependencies via a Directed Acyclic Graph [35].*

By describing a series of conditional independence claims in the form of a directed acyclic graph and a set of probability distributions, the networks encapsulate the probability density on the random variables. Next, we introduce some important concepts for BNs.

Definition 6. *(Parents and children) If there is a directed arc from node a to node b, then node a is a parent of node b and node b is a child of node a. The set of parents of node a is denoted as $Pa(a)$. Similarly, the set of children of node a is denoted as $Ch(a)$. If node a has no parents, i.e. $Pa(a) = \emptyset$, then node a is called a source node.*

If we consider Figure 7.1 again, we see that node 2 is a parent of node 1, node 4, and node 5. Node 5 is a child of node 2, node 3, and node 4. Node 2 is considered as a source node.

Definition 7. *(Ancestors and descendants) If there is a directed path from node a to node b, possibly through other vertices, node b is a descendant of node a and node a is an ancestor of node b. The set of ancestors of node a is denoted by $An(a)$. Similarly, the set of descendants of node a is denoted by $De(A)$.*

Considering Figure 7.1 again, we see that node 5 is a descendent of node 1, or equally node 1 is an ancestor of node 5.

Theorem 5. *(Local Markov Property) Every random variable X_i in a BN is conditionally independent of its ancestors given its parents. Notation:*

$$X_a \perp X_{An(a)} | X_{Pa(a)}.$$

In Figure 7.1 we see that node 5 given its parent node 3 is independent of its ancestor node 1.

The Local Markov Property together with Lemma 4 can be used to simplify the expression of the joint probability as in Equation 7.5.

$$f(x_1, ..., x_n) = \prod_{i=1}^{n} f(x_i | x_{PA(i)}). \tag{7.5}$$

The capacity of the BNs to generate updated distributions, given data, as well as modelling multivariate dependent distributions between the variables, are their key attributes. The ability provide key insights such as prediction, diagnosis, data analysis etc., as well as the easy depiction of the intricate interactions between the random variables, makes the employment of BNs appealing. Thus BNs have a broad application area, such as forensic investigation [36], medical research [37], energy section [38] etc. The use of BN is convenient for the following three reasons according to research [39].

1. Graphical models can be understood clearly and intuitively;
2. Statistical inference is possible through computationally efficient conditioning;
3. Both direct and indirect relationships can be represented.

7.3 Different types of Bayesian Networks

In this section we briefly introduce three different types of Bayesian Networks that are related to the research in this thesis. The first to be discussed Bayesian Network is a Discrete Bayesian Network, also abbreviated with DBN. Next, Continuous Bayesian Networks, CBNs, will be introduced. At last, a mix of a discrete and continuous Bayesian Network will be discussed, which is called a Hybrid Bayesian Network, HBN. The difference in the Bayesian Networks lies in the type of random variables the Bayesian Network is associated with.

7.3.1 Discrete Bayesian Networks

A Discrete Bayesian Network (DBN) is one in which all of the random variables in a BN have discrete distributions. The (marginal) distributions of all source nodes and the conditional probability tables for child nodes complete the quantification of the BN [40]. In the amount of parents, the number of probabilities that must be assessed and preserved for a child node grows exponentially. When a new parent node is added to the network, all of the children's impacts must be reevaluated. If the child node marginal distributions are known, there is no method to directly add this information. Alternatively, conditional probability tables must be adjusted to account for all marginal data [41]. In practice, DBNs have significant limits since the discrete representation of variables offered for many critical situations is insufficient. Therefore DBNs are suitable for only small problems, as illustrated in Section 7.3.1.1.

7.3.1.1 Example: Admission to a University

In this paragraph we consider an example of a DBN from *Edureka by Zulaikha Lateef* [42]. In Figure 7.2 the network is illustrated and models the marks of a student on his examination. There are 5 nodes given in the figure. Consider the node Exam level (E), which is a discrete variable that can take two values. The Exam level can be either difficult or easy. Thus considering the figure, we can see that Exam level is directly connected to Marks (M), meaning that the node Marks is dependent on the Exam level. Next, we have IQ level (I) of the student, which is again a discrete variable that can take two values. The student has either a low IQ or a high IQ. Again, the Marks are directly dependent on the IQ level of the student. Now the marks will in turn predict whether or not a student will get admitted into a University. Thus the probability of a person getting admitted into a University will depend on his marks. That is why there is a direct link from Marks to Admission (A). An additional node that is added to the BN is the aptitude score (S) of the student, which is dependent on the IQ level.

Analyzing the figure further, each node is represented by a (conditional) probability table. Since the Exam level and IQ level are source nodes, they have an unconditional probability, e.g. $P(E = e_0) = 0.7$, whereas the conditional prob-

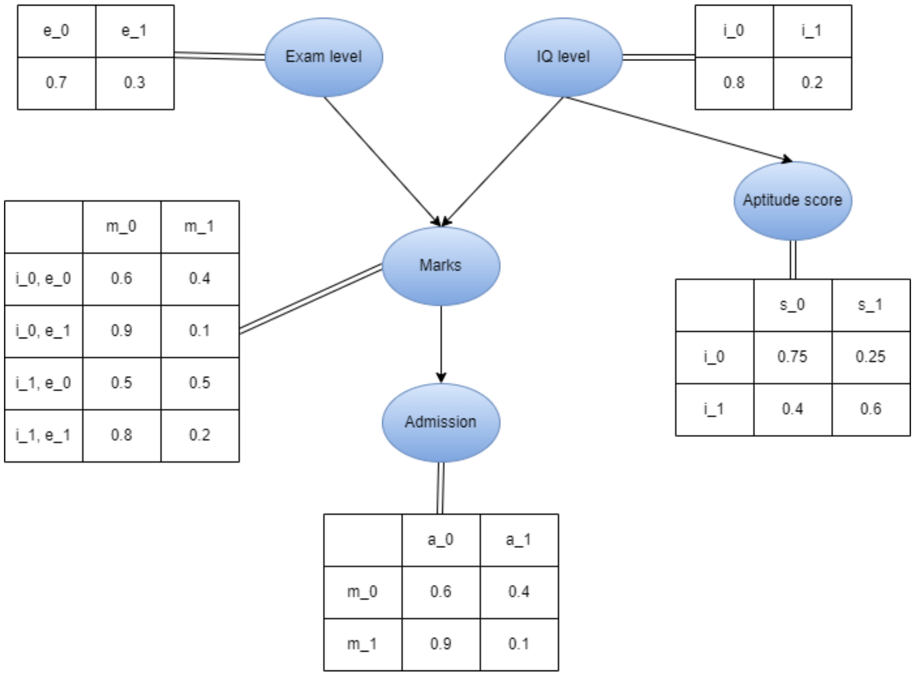

Figure 7.2: Bayesian Network: Admission to a University

ability table for Marks has separate row for each IQ level and Exam level. This is because Marks is directly dependent on IQ level and Exam level. Similarly for the Aptitude score and Admission we see that the conditional probability table has a separate row for IQ level and Marks respectively.

For these discrete random variables we can factorize a joint probability mass function:

$$p(A, M, I, E, S) = p(A|M) \times p(M|I, E) \times p(I) \times p(E) \times p(S|I).$$

In order to find the probability of the Admission score we use the Theorem 2, Law of Total Probability:

$$p(A) = \sum_{\substack{m \in M,\, i \in I \\ e \in E,\, s \in S}} p(A, m, i, e, s) = \sum_{\substack{m \in M,\, i \in I \\ e \in E,\, s \in S}} p(A|m) \times p(m|i, e) \times p(i) \times p(e) \times p(s|i).$$

7.3.2 Continuous Bayesian Networks

A Continuous Bayesian Network (CBN) is one in which all of the random variables are assumed to have continuous distributions. Joint normality is frequently assumed when working with CBNs, and they are referred to as Gaussian BNs. Each node is regressed on the set of its parents, and the impact of a parent on a child is regarded as a regression coefficient. The (conditional) expectations, conditional variances, and regression coefficients of all variables are completely stated in a Gaussian BN model [40].

7.3.3 Hybrid Bayesian Networks

A Hybrid Bayesian Network (HBN) is a form of Bayesian Network (BN) that includes both continuous and discrete random variables. A discrete random variable can only have a discrete random variable as a parent, whereas a continuous random variable can have both discrete and continuous parents [43]. The majority of data in the real-world circumstances requires information about the joint behaviour of discrete and continuous random variables [43], which is also the case in the research of this thesis.

The conditional Gaussian model is one method of dealing with HBNs. The joint Gaussian distribution is a constraint on this type of BN [44]. Discretization is a popular strategy for dealing with continuous variables when the joint normality assumption is not acceptable [45]. To produce a decent approximation while discretizing a continuous variable, a high number of states would be required. In complicated systems, however, this method leads to extraordinarily big conditional probability tables that must be quantified. Because the enormous amount of data necessary for this quantification is rarely accessible, continuous variables are approximated using a small number of states. Furthermore, even if quantification is possible, precise inference may be impossible due to the high number of computations necessary [45].

A second method for dealing with HBNs are the Non-Parametric Bayesian Networks (NPBNs). It was first presented in [46] and then expanded upon in [47] and [48]. By linking marginal distributions of all variables with the dependency structure generated from bivariate dependence, NPBNs construct the joint distribution of a collection of variables represented as a DAG. In NPBNs, nodes are connected with arbitrary distributions, while arcs are associated with (conditional) one-parameter copulae, parameterized by Spearman's rank correlations, see [49] and [50]. The NPBN's arcs are allocated to the (conditioned) copulae using a technique that relies on the parent nodes' ordering. The main discovery of NPBNs is that the joint distribution is uniquely determined by any combination of conditional copulae, one-dimensional marginal distributions, and conditional independence claims supplied by the graph, and that any such specification is consistent, see [51].

7.4 UNINET: basic settings

Before we discuss the stochastic modelling of the Bayesian Network for the uncertainty analysis that is used in this research, we explain some basic features of UNINET. UNINET has been developed by Delft University of Technology and is used to model NPBNs. The primary priority of UNINET is on high-dimensional distribution dependence modeling. This section is based on the UNINET help file [52].

In UNINET there are two kind of nodes that can be modelled: probabilistic nodes and functional nodes. Probabilistic nodes are random variables which are assigned a distribution. Distributions can be selected from a list of available parametric families or can be estimated from data. For this research, data resulting from the SEJ research are used. Probabilistic nodes influences other nodes by if a certain event happens, then another certain event can happen, with a certain probability. As mentioned beforehand, influences among probabilistic nodes is represented by conditional rank correlations [52].

Functional nodes are nodes that are represented as a function of other random variables. The parents of a functional node are the arguments of the function. The parents of the functional nodes can be probabilistic or functional. However, the functional node cannot have a probabilistic child. Functional nodes influences other nodes by if a certain event happens, then another certain event happens.

In Figure 7.3 an example of a functional node is given. Suppose random variables X and Y are probabilistic nodes and following empirical distributions F_x and F_Y, respectively. Random variable Z is defined by the product of random variables X and Y. To take another example from our research project, consider random variable X attaining value 1 when there is a leakage and 0 when there is not a leakage in the hydrogen supply system. Random variable Y attains time values in hours which correspond on how long it takes a mechanic to resolve the corresponding leakage, given the fact that there is indeed a leakage. Then random variable Z attains outcomes of the time when a mechanic is solving the leakage, including the fact that this takes 0 hours, i.e. when there is no leakage.

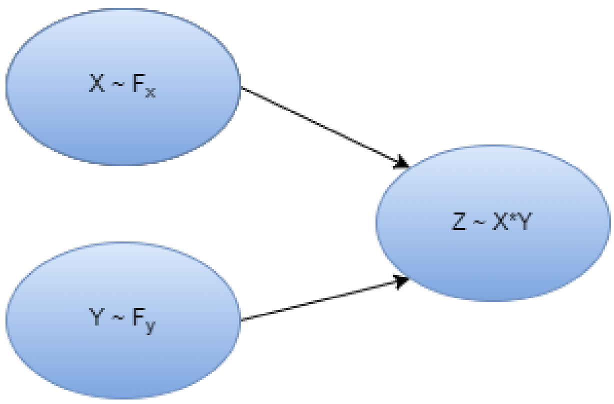

Figure 7.3: Example: Functional node Z, with two probabilistic parent nodes, X and Y.

When the BN is completely defined, we can simulate Monte Carlo samples on the entire joint distributions. Moreover, UNINET enables to represent the nodes using their distributions. It is also possible to condition on a certain variable. The option 'update' in this software makes the network generate conditional exception's which can be used to make predictions.

Chapter 8

Analysis Bayesian Network and Results

In this chapter, we go present the Bayesian Network analysis. Prior to the analysis, we have to specify the structure of the Bayesian Network, which is covered in Section 8.1. In Section 8.2, we discuss how the Bayesian Network is modelled in great depth. In Section 8.3, we execute the analysis in UNINET and provide the key findings. In Section 8.4, we repeat these steps for an extension of the Bayesian Network that was previously utilized. Making a comparison between the outcomes from the SEJ research from Chapter 6 and from the two Bayesian Networks in this chapter, is both fascinating and relevant. As a result, we conclude this chapter with Section 8.5, which includes the comparisons.

8.1 Constructing the structure of the Bayesian Network

In this section we want to model the joint distribution of the random variables discussed Section 3.2.1. This modelling should be consistent with the systematic event influence diagram for hydrogen supply shown in Figure 3.2. To increase readability, the diagram is also repeated in this section in Figure 8.1. Given the assumption that any issues related to the electrolyser or compressor will not influence the hydrogen supply at the buildings in Stad aan 't Haringvliet, we decided not to include them in the risk model. Nevertheless, including them in the Bayesian Network and assuming that we do not always have enough tube trailers, will lead to more insight in the risk assessment. Therefore, as a modest extension of the project, we will take a closer look at it.

In Figure 8.2 a BN is constructed in line with the diagram of Figure 8.1. Given the direction, an ordering of the variables may be formed inside the network, which offers information on the sampling order, i.e. the order in which information is assumed to be obtained. This yields that certain nodes are designated as parent nodes, while others are designated as children nodes. Furthermore, the

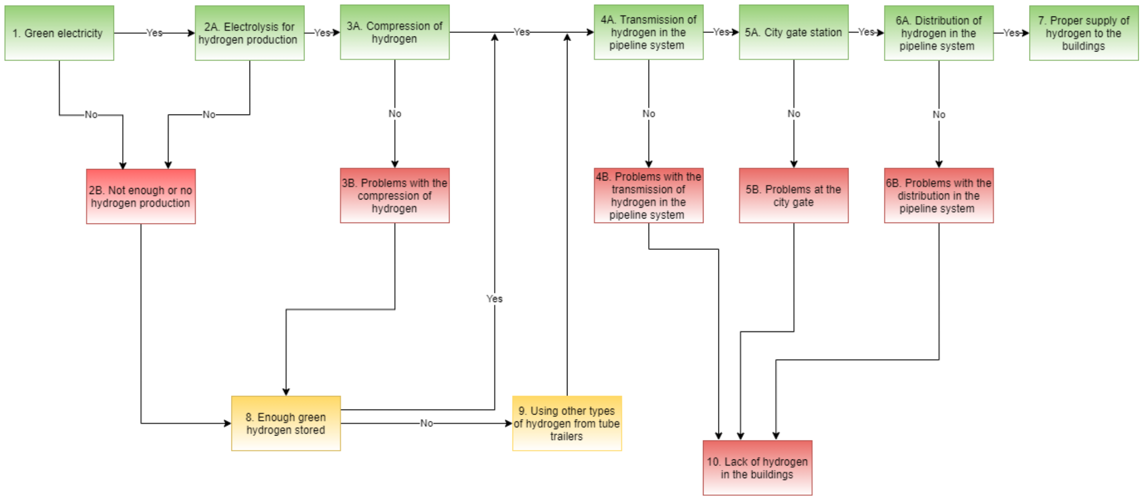

Figure 8.1: Systematic event influence diagram for hydrogen supply

orange/red colored nodes correspond to events indicating possible issues in the system, see Figure 3.2. The blue/green nodes display the time for mechanics to solve the arising issues.

As we see in the BN of Figure 8.2, node A1 and A2 influence B1, i.e. the production of electricity by solar panels and wind turbines influences the production of green hydrogen. Node D1: green hydrogen storage, is dependent on node B1: not enough or no green hydrogen production. It is assumed that if there is not enough or no green hydrogen, green hydrogen from storage needs to be used. If there is not enough green hydrogen stored, then we need to use hydrogen from tube trailers, which is not green, see nodes D1 and D4.

Node NC1 depends on the node C1. If there is a problem with the pressure of hydrogen in the compressor, then a mechanic is needed to solve the problem related to the pressure in the compressor. Node C1 also influences the outcome of node D1. If the pressure of hydrogen is not fixed or the mechanic is working on the problem, then we need hydrogen from the storage in the meantime. Node C1, D1, and D4 both influence the outcome of the pressure of hydrogen in in the transmission pipeline system (node E1). Consequently, if the pressure of hydrogen is too low in the transmission pipeline system, a mechanic is required so that hydrogen attains its right pressure, see node NE1. Node E1 and NE1 affect directly the time having a lack of hydrogen and E1 affects directly the probability when there is a lack of hydrogen. Furthermore, E1 also influence the pressure of hydrogen at the city gate station if the pressure is not at a right value in the transmission pipeline. If this causes a low hydrogen pressure in the city gate station (node F2), then a mechanic is needed for solving this problem (node NF2). The values of nodes F2 and NF2 affect directly the probability and time of having a lack of hydrogen in the buildings. Next, if the pressure is not attained at the right value in the city gate station then this can affect the pressure of hydrogen in the distribution pipeline system at street level. Thus node G3 depends of node F2.

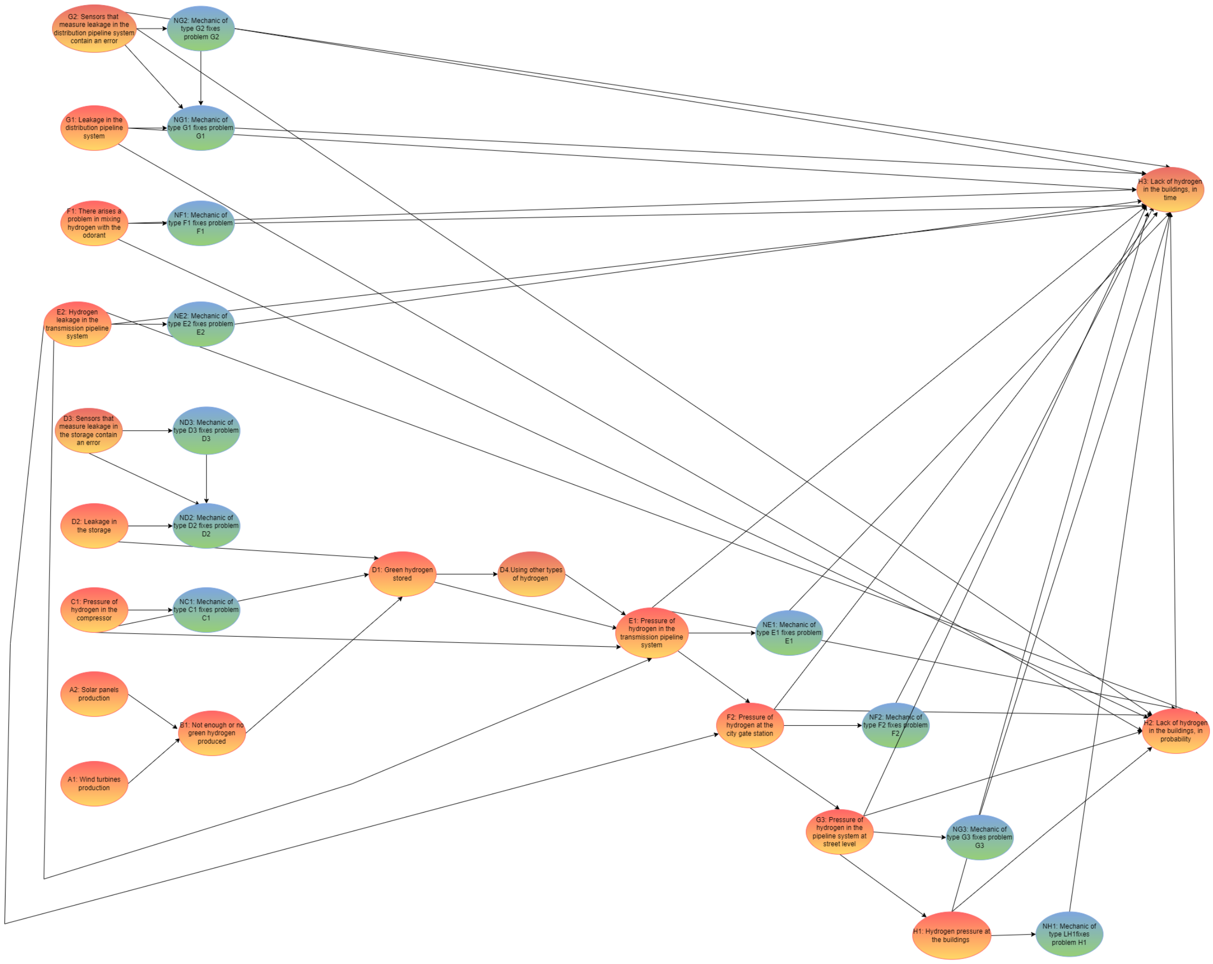

Figure 8.2: Bayesian network: modelling the security of hydrogen supply.

Consequently, if the pressure is too low at street level, a mechanic is required, i.e. NG3 depends on G3. The values of nodes G3 and NG3 affect the probability and time of having a lack of hydrogen in the buildings. Low hydrogen pressure at the buildings is a result of low hydrogen pressure at street level. Thus the nodes G3 influence H1. Hence, node H1 influence NH1, since a mechanic is essential to fix the hydrogen pressure at the buildings if the pressure it too low. Subsequently, node H1 affects directly the probability of a lack of hydrogen in the buildings and together with node NH1 they affect directly the time when there is a lack of hydrogen.

Node D2 represents the event of having a leakage in the storage. If there is a leakage, then a mechanic is needed, see ND2. So node D2 is influencing node ND2. Node D2 also influences node D1: green hydrogen storage. If the leakage occurs then the amount of hydrogen stored will decrease.

Node D3 represents the event that the sensors that measure leakage in the storage contain an error. A mechanic is required to fix the sensors, so it is natural that node ND3 depends on node D3. Both nodes influence the time of a mechanic repairs the leakage in the storage: if there is leakage in the storage and it goes unnoticed since the sensors do not work, then it will take more time for a mechanic with removing the leakage. So node ND2 is dependent on the nodes D3 and ND3.

If there is hydrogen leakage in the transmission pipeline system (node E2), we need a mechanic for this leakage (node NE2). So node NE2 depends on node E2. Subsequently, node E2 also influences nodes E1 and F2, the pressure of hydrogen in transmission pipeline system and city gate station, respectively. Moreover, nodes E2 and NE2 also directly influence the time of having a lack of hydrogen in the buildings, respectively. The probability of having a lack of hydrogen in the buildings is directly affected by node E2.

Node F1 represents the event that a problem in mixing hydrogen with the odorant arises. When there is a problem with the mixing a mechanic is needed to solve this. So node F1 influences node NF1. Node F2 influences node H2 and H3 and node NF2 influences node H3, lack of hydrogen in the homes in probability and time, respectively. H2 represents the lack of hydrogen in homes, in probability, and H3 represents the time, in minutes, there is no hydrogen in homes.

If there is a leakage in the distribution pipeline system (node G1) then a mechanic is essential to remove the leakage (node NG1). This means that node NG1 depends on G1. Node G1 influence nodes H2 and H3 and node NG1 influences node H3 directly.

If there are sensors that measure leakage in the distribution pipeline system that contain an error, we need a mechanic for replacing the sensors or solving the error, in other words: NG2 is dependent of G2. Both nodes influence node NG1. If there is a leakage in the distribution pipeline system and this goes unnoticed because the sensors are not working, then it will take more time to decide a mechanic is needed for the leakage. Furthermore, node G2 and NG3 influence node H3 directly and node G2 also influence node H2 directly.

8.2 Modelling Bayesian Network

Following up on the discussion about the structure of the BN, we will delve a little more into how the BN is modelled in this section. Figure 8.3 depicts the BN that is modelled in UNINET. We notice that the BN in Figure 8.2 has less nodes and arcs than the BN in Figure 8.3. This can be explained due to modeling constraints.

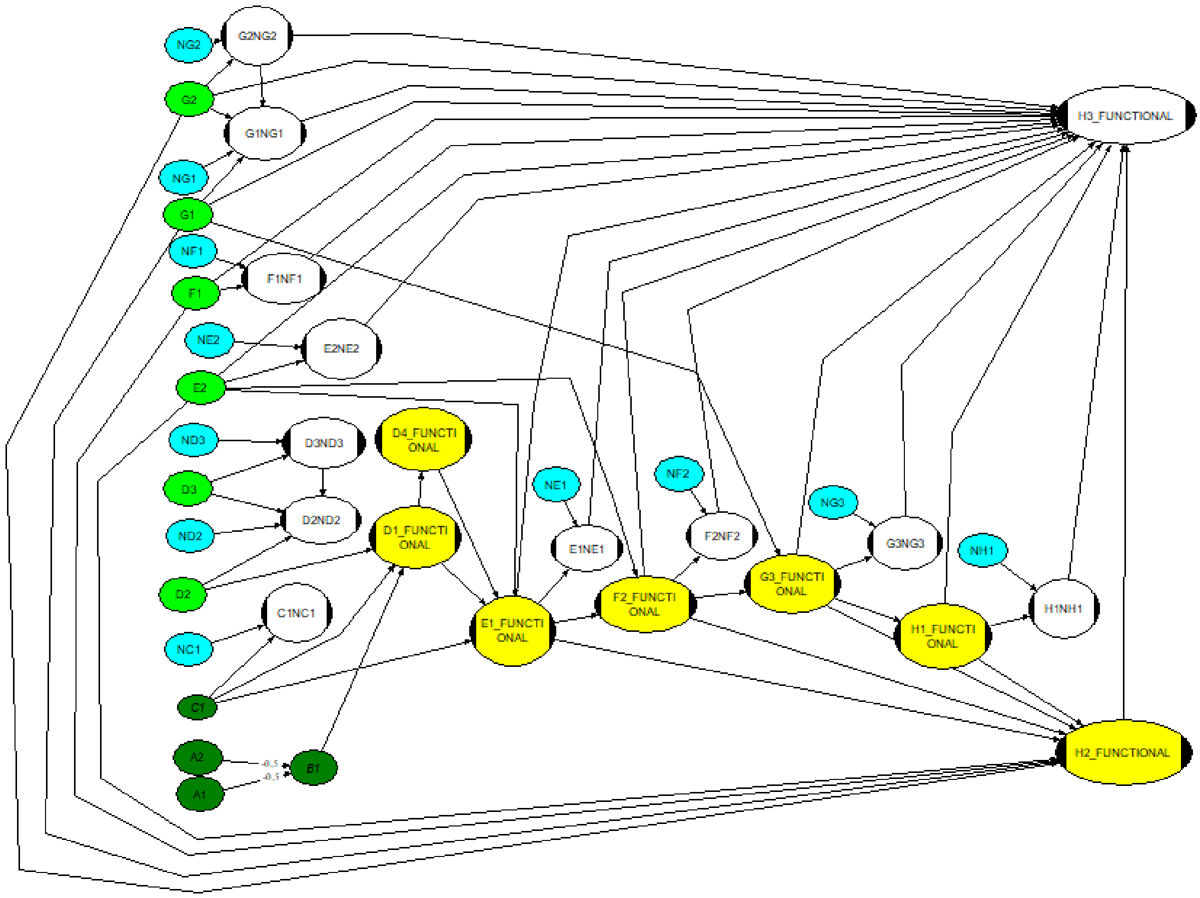

Figure 8.3: Bayesian network from UNINET: the index of the random variables are displayed on the nodes.

The additional nodes are the probabilistic blue nodes given in Figure 8.3. These nodes correspond to time related random variables and whose distributions are quantified from the SEJ research. The additional arcs originate from the blue nodes to the white nodes, i.e. they exert their influence on the white nodes if the event of the blue nodes occur.

The dark green colored nodes correspond to the random variables: A1, A2, B1, and C1, which are assigned a distribution from literature research, see Section 3.2.1. Node B1 depends on node A1 and A2 and they are assumed to have a negative correlation of -0.5, since if one variables increases, the other decreases. This is confirmed by [17], since half of the year green electricity is produced from wind turbines and the other half year generated from solar panels. The light green colored nodes correspond to the random variables: D2, D3, E2, F1, G1, and G2, whose distributions are quantified according to the results from the SEJ research. With exception of node B1, all the (dark) green and blue nodes are parents nodes.

With the exception of node H3, the white nodes relate to the time a mechanic requires to fix an issue and are modelled in the BN only when a problem actually occurs. The matching blue nodes, on the other hand, contain time values depending on the fact that there is a problem. Furthermore, unlike the blue nodes, the white nodes are assigned a function with arguments consisting of blue and dark/light green nodes, rather than an empirical distribution based on the SEJ study results. As a result, the white nodes are functional nodes that exert their influences by causing a given event in the nodes that depend on the white nodes if the white nodes' event occurs.

At long last, the network has yellow nodes. These are functional nodes, which model the relationships among nodes in the influence diagram.

In Tables J.1 and J.2 of Appendix J the formulas for each yellow and white functional nodes are given. These formulas are used in UNINET in order to model the network. Consequently, a derivation can be made from these formulas to probabilities for the random variables. In Appendix K we show how the probabilities for each yellow functional node is derived and in Table K.2 we show how the probabilities for each white functional node corresponding to the time, t, is derived.

8.3 Conditioning analysis for H2 and H3

The constructed structure of the BN, along with the information obtained from SEJ led to the quantification of the variables of interest. The expected probability for having a lack of hydrogen in the buildings is 0.302, with a standard deviation of 0.235. The BN structure allows the interrogation of the network in order to study possible effects of events occurring. It is of interest to analyze how these estimates are updated when we condition on the probabilistic nodes on which H2 depends in the BN. These probabilistic nodes are A1, A2, B1, C1, D2, E2, F1, G1, and G2. In this section we condition on several values for the probabilistic nodes, namely for the value on the 5%, 50%, and 95%- quantiles. With the three values, we want to mimic three scenarios: a best case (for 5% quantile), an estimated case (50% quantile) and a worst case (95% quantile). For the nodes B1 and

C1 we condition on their occurrence. The results are shown in the third column of Table L.1 in Appendix L.

According to Table L.1 in Appendix L, the expected probability for having a lack of supply in the buildings increases for some events. These expected probabilities are colored red in the table. Producing too little green electricity through wind turbines (A1) and solar panels (A2) results in increasing the risk of not having enough hydrogen supply in the buildings. As a consequence, the same statement holds for when there is not enough green hydrogen capacity (B1), the hydrogen pressure in the compressor is too low (C1), there is a hydrogen leakage in the transmission pipeline system (E2), or there arises a problem in mixing hydrogen with the odorant (F1). When there is a leakage in the distribution pipeline system (G1) or sensors that measure leakage in the distribution pipeline system contain an error (G2), the expected probability of having a lack of hydrogen also increases.

Investigating the table further, we see that if the right hydrogen pressure value is not attained in the compressor, the expected probability of having a lack of hydrogen supply in the buildings increases to 0.88. The increase is less rapid for the other red colored rows. The second highest risk is when there is a leakage in the distribution pipeline system with high probability (0.5432). The expected probability increases to 0.617. This is followed by when there arises a problem in mixing hydrogen with the odorant with high probability (0.1354), yielding an expected probability of 0.364 for having a lack of hydrogen supply. The findings are also summarized in Table 8.1, where the problems that increase the expected probability for not having enough hydrogen supply in Stad aan 't Haringvliet are highlighted. The table is ordered from highest increased expected probability to lowest increased expected probability.

In order to address the second objective mentioned Section 1.2, we investigate the analysis for H3. The expected duration for a shortage of hydrogen in the buildings is given in minutes is estimated at 122 minutes with standard deviation of 621 minutes. It is of interest to analyze how the expected time changes when we condition on the probabilistic nodes on which H3 depends in the BN. These probabilistic nodes are A1, A2, B1, C1, D2, E2, NE2, F1, NF1, G1, NG1, G2, NG2, NE1, NF2, NG3, and NH1. In this section we condition on several values for the probabilistic nodes, namely for the value on the 5%, 50%, and 95%- quantiles. For the nodes B1 and C1 we condition on their event value. The results are shown in Tables L.3 and L.4 in Appendix L. According to these tables, the expected time of having a lack of supply in the buildings of Stad aan 't Haringvliet increases for some events. These expected time values are colored red in the tables. Some of the events increase the time value significantly, whereas some only increase it with a small magnitude. In Table 8.2 the events that increase the expected time for not having enough hydrogen supply in Stad aan 't Haringvliet are ordered from highest increased expected time to lowest increased expected time. From this table we conclude that not having the right hydrogen pressure at the com-

Posing biggest problem for hydrogen supply in Stad aan 't Haringvliet	Expected probability for H2
Right pressure of hydrogen in the compressor is not attained	0.88
Hydrogen leakage in distribution pipeline system with high probability (0.5432)	0.617
There arises a problem in mixing hydrogen with the odorant with high probability (0.1354)	0.364
Hydrogen leakage in the transmission pipeline system with high probability (0.06053)	0.361
Sensors that measure leakage in the distribution pipeline system contain an error with high probability (0.1507)	0.353
Not enough or no green hydrogen	0.313
Green electricity production through solar panels with low probability (0.78909)	0.307
Green electricity production through wind turbines with low probability (0.789)	0.306

Table 8.1: Problems that lead to highest expected probability to the lowest expected probability of having a lack of hydrogen.

pressor poses the biggest problem for the disruption of the supply of hydrogen. It is expected that it will result in 2.311E+3 minutes of having a lack of hydrogen in the buildings of Stad aan 't Haringvliet.

8.4 Extending the BN and its modeling

As mentioned in Section 6.2.2 we want a specified pressure value for hydrogen at each component in the hydrogen supply system. However, the pressure does not always need to attain the specified maximum value as discussed in Chapter 3. One of Stedin's staff pointed out that during the summer, the energy demand for heating drops, resulting in a decreased hydrogen supply requirement for the households. Consequently, the pressure of hydrogen in each component of the supply system can be lower than the maximum pressure indicated in Chapter 3. This however is not an issue as long as the hydrogen pressure in each component is not lower than the required pressure in the subsequent component. We may anticipate that if we experience a very harsh winter, the energy demand for heating will be high. For heating, we require additional hydrogen compared to summer/spring. In other words, we require hydrogen at a high pressure, close to or equal to the maximum pressure value for each component of the hydrogen supply system. In this section we show an extension for the BN which takes the low and high hydrogen demand into account.

Posing biggest problem for hydrogen supply in Stad aan 't Haringvliet	**Expected time (in minutes) for H3**
Right pressure of hydrogen in the compressor is not attained	2.31E+3
Mechanic takes 110.3 hours to solve a hydrogen pressure problem in the transmission pipeline system	261
Hydrogen leakage in the distribution pipeline system with high probability (0.5432)	227
Mechanic takes 560 hours to fix issues with sensors that measure leakage in the distribution pipeline system	174
Mechanic takes 25.04 hours to fix issues with leakage in the distribution pipeline system	165
Hydrogen leakage in the transmission pipeline system with high probability (0.06053)	132
There arises a problem in mixing hydrogen with the odorant with high probability (0.1354)	128
Not enough of no green hydrogen produced/ Mechanic takes 1426 hours to fix issues with hydrogen pressure at the city gate station	124
Green electricity production through solar panels with low probability (0.78909)	123

Table 8.2: Problems that lead to highest expected time to the lowest expected time of having a lack of hydrogen.

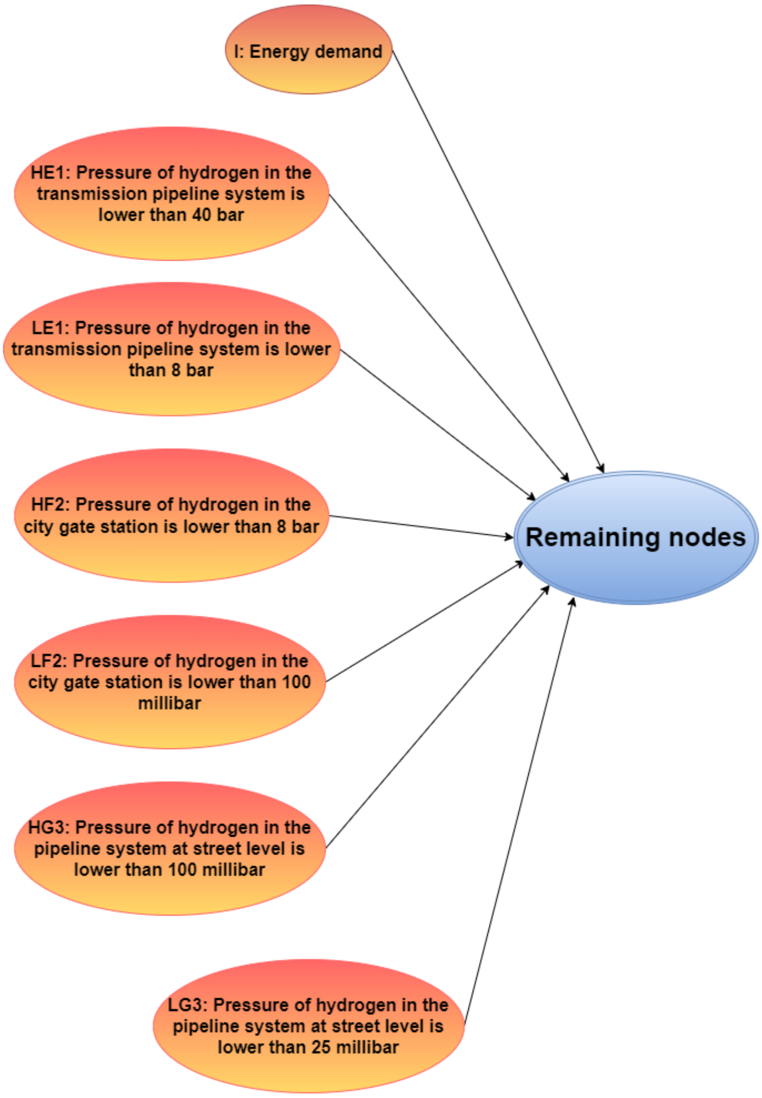

Figure 8.4: Extended Bayesian Network: description of the random variables are stated on the nodes.

By extending the Bayesian Network from Figure 8.3 to an Extended Bayesian Network (EBN) as illustrated in Figure 8.4 we can further model the hydrogen supply system when the energy demand is low or high. The node *I: Energy demand* is assigned a Bernoulli distribution with parameter 0.5, i.e. with probability half the energy demand is low, and with probability half the energy demand is high. Because there are 6 months of autumn and winter (corresponding to months with high energy demand) and 6 months of summer and spring (corresponding to months with low energy demand). Moreover, we introduce 6 additional nodes, to tailor the low/high demand for nodes *E1: Pressure of hydrogen in the transmission pipeline system, F2: Pressure of hydrogen at the city gate station*, and *G3: Pressure of hydrogen in the pipeline system at street level*. This means that we split the node E1 into nodes *HE1: Pressure of hydrogen in the transmission pipeline system is lower than 40 bar* and *LE1: Pressure of hydrogen in the transmission pipeline system is lower than 8 bar*. Note that HE1 is considered for the high energy demand and LE1 is considered for low energy demand. Similarly, we split node F2 from Figure 8.3 into nodes *HF2: Pressure of hydrogen in the city gate station is lower than 8 bar* and *LH2: Pressure of hydrogen in the city gate station is lower than 100 millibar* and the node G3 into nodes *HG3: Pressure of hydrogen in the pipeline system at street level is lower than 100 millibar* and *LG3: Pressure of hydrogen in the pipeline system at street level is lower than 25 millibar*.

In this extension, the six additional nodes have the same parent nodes and child nodes as the original nodes from the network in Figure 8.3. This yields the equalities

$$
\begin{aligned}
Pa(HE1) = Pa(LE1) &= \emptyset \qquad & Ch(HE1) &= Ch(LE1) \\
Pa(HF2) = Pa(LF2) &= \emptyset \qquad & Ch(HF2) &= Ch(LF2) \\
Pa(HG3) = Pa(LG3) &= \emptyset \qquad & Ch(HG3) &= Ch(LG3)
\end{aligned}
$$

In Figure 8.5 we see the EBN that is modelled in UNINET. The only changes in this network when compared to the BN in Figure 8.3 are the additional dark/light green nodes I, LE1, HE1, LF2, HF2, LG3 and HG3. With exception of node I, the distribution of the other nodes is quantified from the SEJ study. When the value of node I equals 0, the functional nodes E1_functional, F2_functional, G3_functional will be influenced by the probabilistic nodes LE1, LF2, and LG3, whereas if the value of node I equals 1, the functional nodes E1_functional, F2_functional, G3_functional will be influenced by the probabilistic nodes HE1, HF2, and HG3.

In Table J.3 of Appendix J the formulas for the functional nodes E1, F2, and G3 from the EBN are given. The formulas for the other functional nodes remain unchanged. Consequently, a derivation can be made from these formulas to probabilities for the corresponding random variables. In Table K.3 of Appendix K we show how the probabilities for these random variables are derived.

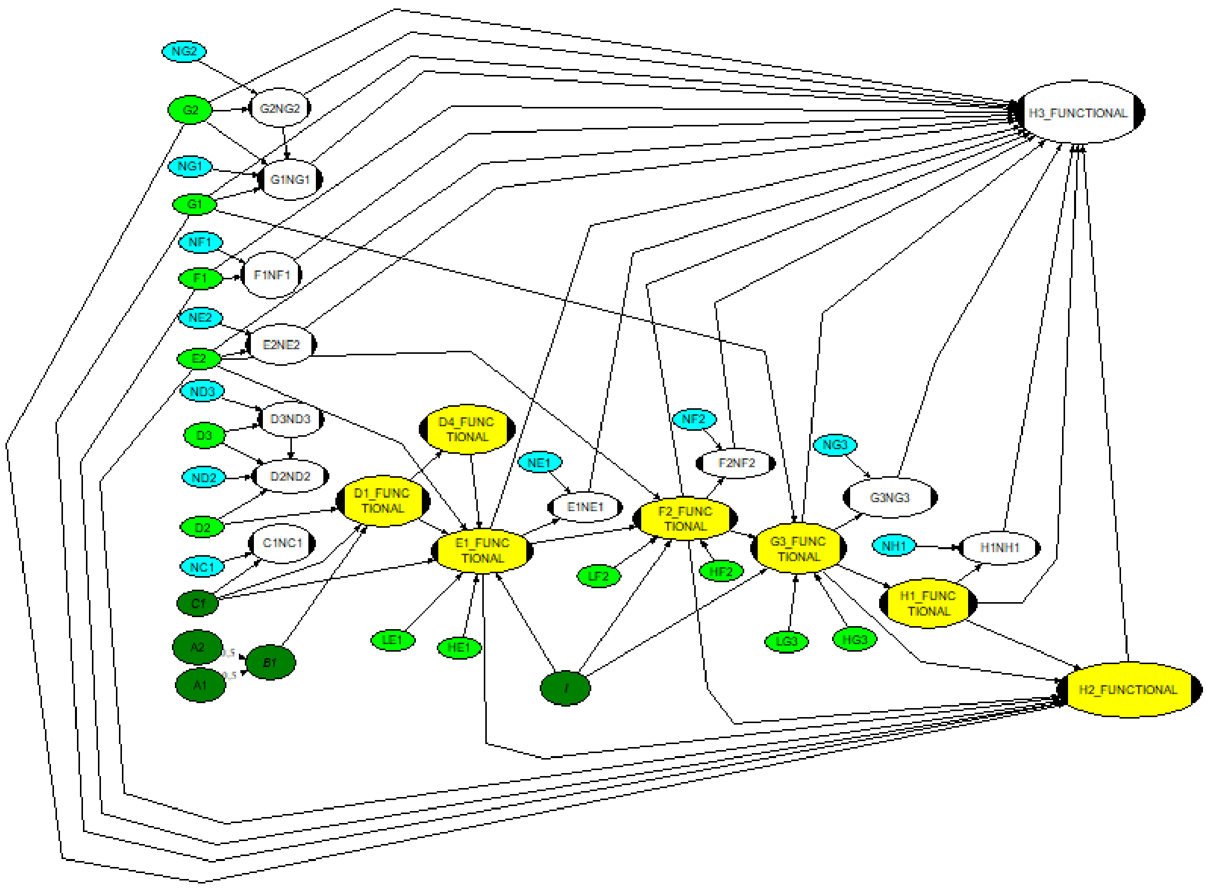

Figure 8.5: Extended Bayesian Network from UNINET: the index of the random variables are displayed on the nodes.

8.4.1 Conditioning analysis for H2 and H3 in EBN

According to the EBN in figure 8.5, the node H2: lack of hydrogen in the buildings, in probability, depends on the same nodes just as before. Namely the nodes: E1, E2, F1, F2, G1, G2, G3 and H1. The expected probability is 0.267 with standard deviation of 0.207. It is quite of interest to analyze how these values change when we condition on the probabilistic nodes on which node H2 depends in the EBN. We consider the same probabilistic nodes as before, together with the nodes I, LE1, HE1, LF2, HF2, LG3, and HG3. Once again, we condition on the values of the 5%, 50% and 95% -quantiles of these nodes, and for B1, C1 and I, we condition on their event value. The results are shown in Tables L.1 and L.2 from Appendix L.

The expected probabilities for having a lack of supply in the buildings increases for some conditioned events. These probabilities are colored red in the tables. In Table 8.3 the problems that increase the expected probability of not having enough hydrogen in the village Stad aan 't Haringvliet are illustrated. The table is ordered from highest increased expected probability to lowest increased expected probability. We observe that the event of having a hydrogen leakage in the distribution pipeline system with high probability (0.5432) poses the highest probability for having a lack of hydrogen supply, namely 0.598. This shows that having a leakage in the distribution pipeline system is seen as the riskiest event for ensuring the security of supply.

Investigating the EBN further for node H3, we have that this node depends on the same nodes as before the extension. The expected time for having a lack of hydrogen in the buildings, in minutes, equals 55.1 with standard deviation of 189. Just as before, we analyze how the expected time changes when we condition on the probabilistic nodes on which H3 depends in the BN. These probabilistic nodes are the same nodes as before the extension of the BN together with the nodes I, LE1, HE1, LF2, HF2, LG3, and HG3. As usual, we condition on the values of the 5%, 50% and 95% -quantiles of these nodes, with exception of nodes B1, C1 and I, where we condition on their event value. The results are shown in Tables L.3 and L.4 in Appendix L.

The expected times for having a lack of hydrogen supply increase for some events when we condition on them. These time values are colored red in Tables L.3 and L.4. In Table 8.4 the problems that increase the expected time of not having enough hydrogen supply in the city are shown. The results in the table is ordered from highest increased expected time to lowest increased expected time. It shows us that not having the right hydrogen pressure at the compressor poses the biggest treat, since it leads to 231 minutes of not having enough hydrogen in the buildings of Stad aan 't Haringvliet.

Posing biggest problem for hydrogen supply in Stad aan 't Haringvliet	**Expected probability for H2 in EBN**
Leakage in the distribution pipeline system with high probability (0.5432)	0.598
Pressure of hydrogen in the compressor is not attained	0.39
There arises a problem in mixing hydrogen with the odorant with high probability (0.1354)	0.333
Sensors that measure leakage in the distribution pipeline system contain an error with high probability (0.1507)	0.321
Hydrogen leakage in the transmission pipeline system with high probability (0.06053)	0.302
Not having the right hydrogen pressure at the transmission pipeline system with high probability (0.9322) when the hydrogen supply demand is high	0.282
High energy demand	0.273
Not enough or no green hydrogen produced/ Hydrogen leakage in the storage with high probability (0.08035)	0.271
Not having the right hydrogen pressure at the transmission pipeline system with high probability (0.1746) when the hydrogen supply demand is low	0.27
Green electricity production through solar panels with low probability (0.78909)/ Green electricity production through wind turbines with low probability (0.789)	0.269

Table 8.3: Problems that lead to highest expected probability to the lowest expected probability of having a lack of hydrogen.

Posing biggest problem for hydrogen supply in Stad aan 't Haringvliet	**Expected time (in minutes) for H3 in EBN**
The right pressure of hydrogen in the compressor is not attained	231
Hydrogen leakage in the distribution pipeline system with high probability (0.5432)	157
Mechanic takes 560.4 hours to fixes issues with the sensors that measure leakage in the distribution pipeline system	104
Mechanic takes 25.04 hours to fixes issues with leakage in the distribution pipeline system	97.2
Sensors that measure leakage in the distribution pipeline system contain an error with high probability (0.11507)	85
Not having the right hydrogen pressure at the transmission pipeline system with high probability (0.9332) when the hydrogen supply demand is high	79.8
Mechanic takes 110.3 hours to solve a hydrogen pressure problem in the transmission pipeline system	66.5
There arises a problem in mixing hydrogen with the odorant with high probability (0.1354)	61.8
High energy demand	61.3
Hydrogen leakage in the transmission pipeline system with high probability (0.06053)	59
Leakage in the storage with high probability (0.08035)	55.9
Not enough or no green hydrogen produced/ Mechanic takes 46.28 hours to fixes issues with leakage in the transmission pipeline system/ Mechanic takes 12.68 hours to fixes issues with mixing odorant with hydrogen	55.7
Not having the right hydrogen pressure at the transmission pipeline system with high probability (0.1746) when the hydrogen supply demand is low	55.6
Green electricity production through solar panels with low probability (0.78909)	55.4
Green electricity production trough wind turbines with low probability (0.789)	55.3

Table 8.4: Problems that lead to highest expected time to the lowest expected time of having a lack of hydrogen.

8.5 Comparison of results

In this section we compare the results for the random variables H2 and H3 for three different studies. The first study is from Chapter 6 and will be referred as the SEJ research. We use the results of the first two questions of interest for the comparison. The second study is from the BN in this chapter. We will refer to this study as the BN research. At last, the third study will use the results from the EBN, also from this chapter. We refer to this study as the EBN research.

The 5, 50, and 95%-quantiles for the random variables in the three types of research are presented in Table 8.5. When comparing the outcomes of the BN and EBN research, we can observe that the EBN leads to smaller expected probabilities and times. This makes sense since, in the BN research, we constructed the network with the constraint that we require the maximum pressure value or we would have a problem, whereas this was not the case with the EBN.

	H2			H3		
Research	q_5	q_{50}	q_{95}	q_5	q_{50}	q_{95}
BN	0.03099	0.2339	0.8266	4.138E-3	5.006	386.2
EBN	0.02597	0.2067	0.6494	2.32E-3	3.135	259.8
SEJ	0.003761	0.06839	0.5373	0.1001	114	55310

Table 8.5: Results for H2 and H3, using the researches SEJ, BN, and EBN.

Furthermore, the UNINET findings reveal that the probabilities of a hydrogen shortage in buildings are higher than those found in the SEJ research. Concerning how long the buildings will be without hydrogen yields different values for each research. Focusing on the 50%-quantile, we observe that the BN, EBN, and SEJ researches warn us that the lack of hydrogen in Stad aan 't Haringvliet will take 5, 3, and 114 minutes in the first year of realizing Stedin's pilot, respectively.

For several random variables, the BNs modelled in UNINET used distributions derived from the SEJ research. Therefore, one might expect that the probabilities and time values in Table 8.5 are close to each other. It can be explained why this is not the case. To begin with, the experts from the SEJ research merely considered the model assumptions. Furthermore, the biases of each expert should also be taken into account. Another factor to consider is that the functional nodes are provided with a formula that corresponds to the systematic event influence diagram for hydrogen supply (see Figure 8.1). The outcomes of these formula can differ significantly from the answers of the expert in the SEJ research. For example, some experts believe that the system's production side will represent the greatest danger to hydrogen supply. However, production was not considered as a threat, according to the hydrogen supply system. This was not the objective when the hydrogen supply system was modelled. Despite everything, we still chose to condition on the nodes from the production side in the BNs, for more insights.

Hence the following question arises: Which study should be used to establish the conclusions for this thesis? Despite the fact that the SEJ research is an important aspect of this thesis and its findings are integrated in the BN and EBN researches, we should not utilize the SEJ research to draw conclusions. Some experts were debating the components of the hydrogen supply system in ways that were inconsistent with the premises of the hydrogen supply system, and the working assumption is that this system is considered to be correct for this thesis research. Furthermore, the calibration scores indicated that the assessments were modest in terms of statistical accuracy. Moreover, most random variables in the UNINET networks are constructed only using mathematical reasoning, e.g. formulas assigned to the functional nodes, or how the arcs are connected with the nodes. This makes it more convenient to prefer the studies from UNINET over the SEJ research, given that human judgment can be subjected to biases. Since in the EBN research we make an extra assumption which better fits reality than the BN research, it is evident to give the preference to the EBN research over the BN research for answering the main problems in this thesis research.

This yields the following conclusions: The best estimate for how likely it is that there is not enough hydrogen in the buildings equals 0.2067, with a 90% confidence interval [0.02597,0.6494], according to the EBN research. And considering the event of not having enough hydrogen in Stad aan 't Haringvliet, the best estimate for how long this last in minutes is 3.135 minutes, with 90% confidence interval [2.32E-3,259.8], in the first year of realizing Stedin's pilot.

Comparing the results from the EBN research with the number used for natural gas in Section 6.5.1, we observe that the answers for the first question are far from each other. The present research indicates that hydrogen supply system has the potential to be less secure than the natural gas supply system. Nevertheless, this high probability might originate from the SEJ research. It was evident from the calibration questions that experts were overestimating, even when they were trying to assign low probabilities/rates to these questions, e.g. assigning a numerical value of 0.1 instead of 10^{-6}. They may have done the same thing for the questions of interest. For the second question, the best estimate for hydrogen shortage equals 3.135 minutes, whereas the numbers for the natural gas instances from Section 6.5.1 stated a significantly longer duration of shortage. Thus it can also be argued that the present research indicates that the hydrogen supply system has the potential to be more secure than the natural gas supply system.

Chapter 9

Conclusion

We conclude this thesis by summarizing the key results of the thesis, followed by a discussion, and ending with suggestions for further research.

9.1 Summary of the results

In this thesis we aimed to quantify the risk to 100% hydrogen supply security in the built-environment and, when feasible, compare it to the natural gas security of supply. We established a model called the hydrogen supply system, which is built using Stedin's criterion, see Figure 9.1. On the basis of this model we have constructed random variables that needed to be quantified. The random variables corresponds to the addressed risks and times a mechanic needs to solve a issue. Next, the Classical Model for Structured Expert Judgment is used to predict the threats to hydrogen supply security in the city of Stad aan 't Haringvliet. Afterwards, the results from the Classical Model for Structured Expert Judgement are integrated in Bayesian Networks.

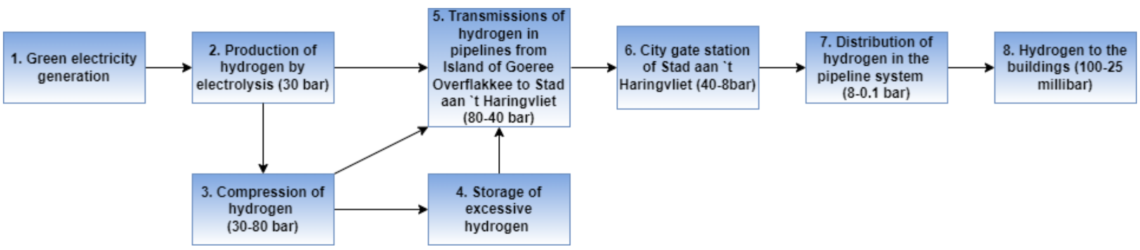

Figure 9.1: System for hydrogen supply.

The results from the Structured Expert Judgement research reveal that the best estimate for how likely it is that there is not enough hydrogen in the buildings equals 0.06839, with 90% confidence interval [0.003761, 0.5373]. Using average data from 2013 to 2017 from the website of Netbeheer Nederland, we can conclude that the corresponding probability for natural gas is 0.007. There are several reasons why the obtained probability for hydrogen is higher than that for natural gas, which have been detailed in Section 8.5. The foreseen challenges posed by hydrogen production are arguably the biggest contributor to the increase in probability. However, this probability is captured in the confidence interval for hydrogen.

When considering the event of not having enough hydrogen in the buildings of Stad aan 't Haringvliet the best estimate for how long this lasts in minutes is 114 minutes, with 90% confidence interval [0.1001, 5.531E006]. Using data from the Dutch regional grid for natural gas in 2018, we estimate that the total time spent without natural gas in buildings in 2018 was 135 minutes and 41 seconds. The SEJ study estimate for hydrogen and the time for natural gas in 2018 are nearly identical.

Impact
Minor
Moderate
High

Likelihood for the risks		
Low	Medium	High
Sensor error in the storage	Sensor error in the distributional system	Hydrogen leakage in the distributional system
Hydrogen leakage in the storage	Hydrogen leakage in the tranmission system	Hydrogen pressure drop in the transmission system
Hydrogen pressure drop in the buildings	Hydrogen pressure drop in the city gate station	
	Hydrogen pressure drop in the distributional system	

Figure 9.2: Likelihood and impact of the riks in the hydrogen supply system

Comparing the failure rate between the components from the hydrogen supply system using the results from the SEJ research and the individual assessment of the experts leads to the table in Figure 9.2. The table summarizes the likelihood of the risks, obtained from experts, that have been examined. The assignations of the impact (severity of the risk) and likelihood of risk have been detailed in Section 6.5.2. According to Figure 9.2, the biggest treats for the hydrogen supply system are hydrogen leakages in the distributional system and hydrogen pressure drop in the transmission system.

Next, a table is illustrated in Figure 9.3, which shows for every risk from the hydrogen supply system one or more mitigations. These mitigations could be realized in order to improve the security of hydrogen supply in Stad aan 't Haringvliet.

Implementing the obtained distributions from the SEJ research in the BN and EBN researches give results for random variables H2 and H3 which are not in

Risk mitigation	
Risk	**Mitigation**
Sensor error in the storage	Sensors should be calibrated at least once a month, and duplicate sensors should be kept on hand.
Sensor error in the distributional system	Sensors should be calibrated at least once a month, and duplicate sensors should be kept on hand.
Hydrogen leakage in the distributional system	A team of professionals from Stedin should be deployed to assist with the excavucations.
Hydrogen pressure drop in the transmission system	Sensors should be installed in the transmission system and more maintenainces should be scheduled.
(Problems at the production of hydrogen)	(Increase redundacy in hydrogen storage or hydrogen capacity overall)

Figure 9.3: This tables shows for every risk from the hydrogen supply system one or more mitigations.

line with the results for the SEJ research, see Table 9.1. When conditioning on the probabilistic nodes in the EBN, we obtained the following findings.

	H2			H3		
Research	q_5	q_{50}	q_{95}	q_5	q_{50}	q_{95}
BN	0.03099	0.2339	0.8266	4.138E-3	5.006	386.2
EBN	0.02597	0.2067	0.6494	2.32E-3	3.135	259.8
SEJ	0.003761	0.06839	0.5373	0.1001	114	55310

Table 9.1: Results for H2 and H3, using the researches SEJ, BN, and EBN.

The event of having a leakage in the distribution pipeline system with high probability (0.5432) was found to be the most problematic for hydrogen supply. The expected probability for H2 will increase from 0.267 to 0.598. When we assume that there is a lack of hydrogen supply in the buildings, we discovered that not having the right hydrogen pressure at the compressor posed the most significant difficulty for the duration of hydrogen shortage. The expected time rose from 55.1 to 231 minutes.

Furthermore, after considerable deliberation, we conclude that the EBN research is employed to address the thesis's primary issues. As a result, we obtain answers for the thesis key goals:

1. *How likely is it that there is not enough hydrogen in the buildings of Stad aan 't Haringvliet in the first year of realizing Stedin's pilot, in probability?*
Answer: The best estimate for this probability equals 0.2067 with 90% confidence interval [0.02597,0.6494].

2. *Consider the event of not having enough hydrogen in the buildings of Stad aan 't Haringvliet. How long do you expect this to last in the first year of realizing Stedin's pilot, in minutes?*
Answer: The best estimate for for how long this will last equals 3.135 minutes with 90% confidence interval [2.315E-3,259.8].

Comparing the results from the EBN research with the number used for natural gas in Section 6.5.1, we observe that the answers for the first question are far from each other. The present research indicates that hydrogen supply system has the potential to be less secure than the natural gas supply system. However, it was evident from the calibration questions that experts were overestimating, even when they were trying to assign low probabilities/rates to these questions, e.g. assigning a numerical value of 0.1 instead of 10^{-6}. They may have done the same thing for the questions of interest. Next, for the second question, the best estimate for hydrogen shortage equals 3.135 minutes, whereas the numbers for the natural gas instances from Section 6.5.1 stated a significantly longer duration of shortage. Thus it can also be argued that the present research indicates that the hydrogen supply system has the potential to be more secure than the natural gas supply system.

9.2 Discussion

In this section we point out potential limitations of the hydrogen supply system, Structured Expert Judgement study, and the Bayesian Network studies. The critical comments about the research are covered below:

- We have limited the scope of this project since the full risk account would have been too complex. This implies that we did not account for every conceivable risk (for hydrogen supply) as well as other factors that could help solve problems if they arise. We also did not go into great depth about each component because, for example, the electrolysis of hydrogen is a large topic on its own. It would, however, be of interest to further detail components.

- The experts' performance-based weights, and hence the DMs' scores, were all quite low. The forecasts would be more trustworthy if the scores were higher. Having access to a larger pool of experts could help improve the SEJ results.

- Some of the calibration questions should have been phrased more clearly. Questions having a probability close to zero, for example, were answered with 0.1 or 0.00001. Both responses are near to zero, yet their magnitudes are vastly different. We can achieve greater scores by letting experts know what magnitude they are dealing with.

- The number of experts accessible for this master's thesis was restricted. We could have gathered more qualified experts if there had not been any practical obstacles, such as time.

- When we discussed the findings of the SEJ study with Stedin, one expert told us that he does not expect much digging at Stad aan 't Haringvliet since it is regarded as a sleeping town. This crucial information was left out of both the project description and the elicitation protocol. However, many of the consulted experts considered excavating to be one of the greatest risks to the hydrogen supply. As a consequence, this has an effect for the results in the SEJ research.

- The results for the hydrogen case and the natural gas case could not be compared appropriately, since there was no credible material available. The data from *Netbeheer Nederland* [28] were not based on a sleepy small village like Stad aan 't Haringvliet, but rather on the whole country.

- While conditioning for the random variables H2 and H3, we only restricted by fixing one random variable to a certain value. However, UNINET allows the option where you can fix more random variables at the same time. This type of analysis may provide us with additional insight into risk assessment.

9.3 Future Work

Following the completion of this work, various proposals for follow-up studies emerged. In this part, we will go through the steps that might be taken in the future for future work.

- At the moment, the production is assumed safe, with both green energy, storage and tube trailers assuring hydrogen at all times. This however, is not in agreement with experts'. For future work we can start assuming that the production side of the hydrogen supply system can pose problems and go deeper in-depth. In this thesis we have been restrictive with the production side.

- Next, begin by examining the sub-systems of the hydrogen supply system in further depth. Then, by identifying additional risks and factors that would solve issues if they arose, the model becomes more advanced and more accurate. For example, in Section 2.2.2 it was mentioned that the received hydrogen can be pure or impure. In this thesis we assumed that hydrogen was pure at all cost. Thus, for the future work we can take the quality of received hydrogen into account.

- Taking the following assumption into account in the elicitation protocol: Stad aan 't Haringvliet is considered as a sleeping town and not much digging is expected.

- While performing the uncertainty analysis using Bayesian Networks, we could fix more random variables at the same time in order to gain more insights into the behaviour of the hydrogen supply network. For example, we showed that high demand is seen as the riskiest setting for ensuring the security of supply. An interesting insight would have been to condition on the high demand, and then on all other 'issues', and see which one leads to the highest increase. A similar analysis can be performed for the low demand instance.

Bibliography

[1] Abigail R. Colson, Roger M. Cooke, *Expert Elicitation: Using the Classical Model to Validate Experts' Judgments*, 02/02/2018.

doi.org/10.1093/reep/rex022

[2] Jason Brownlee, *A Gentle Introduction to Bayesian Belief Networks*, 11/10/2019.

URL machinelearningmastery.com/introduction-to-bayesian-belief-networks/

[3] Stedin, *Waterstof, we onderzoeken het*.

URL stedin.net/over-stedin/duurzaamheid-en-innovaties/waterstof

[4] Stedin en Kiwa,*Van aardgas naar waterstof. De overstap van Stad aan het Haringvliet*.

URL kiwa.com/globalassets/netherlands/kiwa-technology/downloads/publicatie-ombouw-waterstof-stad-aan-t-haringvliet.pdf

[5] De Wereld Van Waterstof, Gasunie, *Waterstof in de historie*.

URL dewereldvanwaterstof.nl/gasunie/historie/

[6] Energy Cities, The European association of cities in energy transition, *50 shades of (grey and blue and green) hydrogen*.

URL energy-cities.eu/50-shades-of-grey-and-blue-and-green-hydrogen/

[7] TNO, innovation for life, *15 things you need to know about hydrogen*.

URL tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/hydrogen-for-a-sustainable-energy-supply/15-things-you-need-to-know-about-hydrogen/

[8] Stichting StadsWeb,*StadsWeb, meer dan droag brood*, 2021.

URL stadaantharingvliet.nl/site/

[9] Guest Contributor, *Is Hydrogen The Best Option To Replace Natural Gas In The Home? Looking At The Numbers*, 14/12/2020.

URL `cleantechnica.com/2020/12/14/can-hydrogen-replace-natural-gas-looking-at-the-numbers/`

[10] D. Gardner, Renewable Energy Focus, *Hydrogen production from renewables* , 1/1/2009.

URL `renewableenergyfocus.com/view/3157/hydrogen-production-from-renewables/`

[11] A.A.C. van Vliet, L. Gooijer, G.M.H. Laheij, *On-site natural gas piping Scenarios and failure frequencies Report*, 2011.

[12] KYOS Energy Consulting, *What is a green certificate?*, 2022.

URL `www.kyos.com/faq/green-certificate/`

[13] Johns Hopkins, School of Advanced International Studies, *Renewable Energy vs Sustainable Energy: What's the Difference?*, 2/7/2021.

URL `energy.sais.jhu.edu/articles/renewable-energy-vs-sustainable-energy/`

[14] Kevin Harrison, *Onrel Transforming Energy, Renewable Electrolysis*, 2017.

URL `nrel.gov/hydrogen/hydrogen-production-delivery.html`

[15] Olle Michel Kam,Stephane Noël, Harry Ramenah, Pierre Kasser, Camel Tanougast, *Comparative Weibull distribution methods for reliable global solar irradiance assessment in France areas*, 7/11/2020, DOI: 10.1016/j.renene.2020.10.151.

[16] A. J. M. van Wijk, N. Halberg and W. C. Turkenburg, *Capacity credit of wind power in the Netherlands*, May 1992, doi.org/10.1016/0378-7796(92)90087-H.

[17] Pure energie, *Zonnepanelen en windmolens: wat is beter?*.

URL `pure-energie.nl/kennisbank/zonnepanelen-vs-windmolens/`

[18] M. Casamirra, F. Castiglia, M. Giardina, C. Lombardo, *Safety studies of a hydrogen refuelling station: Determination of the occurrence frequency of the accidental scenarios*, July 2009, doi.org/10.1016/j.ijhydene.2009.01.096.

[19] Julien Mouli-Castilloa, et al. *A comparative study of odorants for gas escape detection of natural gas and hydrogen*, 19/4/2021, doi.org/10.1016/j.ijhydene.2021.01.211.

[20] Stedin, *Investeringsplan*, 2020-2022.

[21] Stedin, *Kwaliteits- en capaciteitsdocument elektriciteit*, 2018-2020.

[22] Mehmet E. Biresselioglu et al., *Investigating the natural gas supply security: A new perspective*, 18/12/2014, doi.org/10.1016/j.energy.2014.11.060.

[23] Meysam Qadrdan et al., *A model for investigation of optimal hydrogen pathway, and evaluation of environmental impacts of hydrogen supply system*, 14/5/2008, doi.org/10.1016/j.ijhydene.2008.09.031.

[24] Rjwerf, 2020.

URL `rjwerf.nl/wp-content/uploads/2013/12/gasnet.jpg`

[25] Ni Meng et al. *Potential of renewable hydrogen production for energy supply in Hong Kong*, 13/12/2005, DOI:10.1016/j.ijhydene.2005.11.005.

[26] S.S. Penner, *Steps toward the hydrogen economy*, 2006, doi:10.1016/j.energy.2004.04.060.

[27] British Petroleum (BP), *BP statistical review of world energy*, 2014.

URL `bp.com/statisticalreview`

[28] Netbeheer Nederland, *Hoofdstuk 2: Betrouwbaarheid energievoorziening*, 2022.

URL `energiecijfers.info/hoofdstuk-2/`

[29] Stedin, *The world we live in, Annual report*, 2018.

[30] Abdi H. et al., *Wiley interdisciplinary reviews: computational statistics*, 2010, Online ISSN:1939-0068.

[31] Mooc, *Decision Making Under Uncertainty: Introduction to Structured Expert Judgment*, 2020.

URL `courses.edx.org/courses/course-v1:DelftX+SEJ1x+1T2020/course/`

(course followed in May 2020).

[32] Anca M. Hanea, Gabriela F. Nane, *An In-Depth Perspective on the Classical Model*, 2021 DOI:10.1007/978-3-030-46474-5_10.

[33] R.M. Cooke, *Experts in uncertainty: Opinion and subjective probability in science. Environmental Ethics and Science Policy Series*, 24/10/1991.

[34] Excalibur glossary, 29/6/2021.

URL `vhub.org/resources/3986/download/ExcaliburGlossary.pdf`

[35] A.M. Hanea, Delft University of Technology, *Doctoral Thesis: Algorithms for Non-Parametric Bayesian Belief Nets*, 2008.

[36] A.Biedermann, F.Taroni, *Bayesian networks for evaluating forensic DNA profiling evidence: A review and guide to literature*,2/03/2012, doi.org/10.1016/j.fsigen.2011.06.009.

[37] T. Yue, T. Zhang, *Bayesian network-based missing mechanism identification (BN-MMI) method in medical research*, 12/11/2021, doi.org/10.1186/s12911-021-01677-6.

[38] Yuanjiang Chang et al., *Dynamic Bayesian network based approach for risk analysis of hydrogen generation unit leakage*, 8/10/2019, doi.org/10.1016/j.ijhydene.2019.08.065.

[39] D. Margaritis, School of Computer Science, Carnegie-Mellon University, *PhD thesis:Learning Bayesian Network Model Structure from Data*, 2003.

[40] F.D. Bookholt, P. Stuurman, A.M. Hanea, *Practical Guidelines for Learning Bayesian Networks from Small Data Sets*, 13/1/2014, doi.org/10.4236/oalib.1100481.

[41] Uninet help file, *UNINET Help*.

URL `lighttwist-software.com/wp-content/doc/UninetHelp.pdf`

[42] Zulaikha Lateef, *How To Implement Bayesian Networks In Python, Bayesian Networks Explained With Examples*, 25/11/2020.

URL `edureka.co/blog/bayesian-networks/`

[43] B. Naveen Kumar, P. V. Kumar, *Learning Parameters for Hybrid Bayesian Network*, 1/12/2020, DOI: 10.1007/978-3-030-49795-8_25.

[44] B. Yet et al., *An improved method for solving Hybrid Influence Diagrams*, April 2018, doi.org/10.1016/j.ijar.2018.01.006.

[45] K. Murphy, Technical Report, Intel Research, *An introduction to graphical models*, 2002.

[46] D. Kurowicka, R. Cooke,*Distribution-free continuous Bayesian belief nets*, 2005, doi.org/10.1142/9789812703378_0022.

[47] A. M. Hanea, D. Kurowicka, R. M. Cooke, *Hybrid Method for Quantifying and Analyzing Bayesian Belief Nets*, 24/08/2006, doi.org/10.1002/qre.808.

[48] A.M.Hanea, D.Kurowicka, R.M.Cooke, D.A.Ababei, *Mining and visualising ordinal data with non-parametric continuous BBNs*, 1/03/2010, doi.org/10.1016/j.csda.2008.09.032.

[49] H. Joe, *Multivariate Models and Multivariate Dependence Concepts*, 1997.

[50] Roger B. Nelsen, *An Introduction to Copulas*, 2006.

[51] A. Hanea, D. Kurowicka and R. Cooke, *Hybrid method for quantifying and analyzing Bayesian belief nets*, 24/08/206, doi.org/10.1002/qre.808

[52] TU Delft, *Uninet*.

URL tudelft.nl/ewi/over-de-faculteit/afdelingen/applied-mathematics/applied-probability/research/research-themes/risk/software/uninet

[53] Stedin, *Deep Drive Herijking Bedrijfswaardenmodel*, 16,17/11/2020.

[54] Wind Europe, *Wind energy in Europe 2020 Statistics and the outlook for 2021-2025*.

URL windeurope.org/intelligence-platform/product/wind-energy-in-europe-in-2020-trends-and-statistics/

[55] SolarPower Europe, *Global Market Outlook for solar power for 2021-2025*, July 2021.

URL solarpowereurope.org/wp-content/uploads/2021/07/SolarPower-Europe_Global-Market-Outlook-for-Solar-2021-2025_V1.pdf

[56] M. A. Khan, I. Al-Shankiti, A. Ziani and H. Idriss, *Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability*, 6/1/2021, DOI: 10.1039/d0se01761b.

[57] Statista, *Natural gas consumption in the Netherlands from 2005 to 2020*, 2022.

URL statista.com/statistics/703665/natural-gas-consumption-netherlands/

[58] Stedin, *Crucial craftsmanship, Extract Annual Report*, 2020.

[59] Deborah Keeley, *Failure rates for underground gas storage*, 2008.

URL hse.gov.uk/research/rrpdf/rr671.pdf

[60] M. W. Melaina, O. Antonia, and M. Penev, Ornel, *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*, March 2013.

URL nrel.gov/docs/fy13osti/51995.pdf

Appendix A

Random variables from the hydrogen supply system

Below a table is given about the random variables to the events that are considered in each component of the hydrogen supply system, see Figure 3.1. They are quantified as much as possible, without the use of Structured Expert Judgement (SEJ).

Random Variable	Quantification	Support
A1: Wind turbines production	production $\sim$ Wei$(0.8, 216)$	$[0, \infty)$ kWh
A2: Solar panels production	production $\sim$ Wei$(0.8, 216)$	$[0, \infty)$ kWh
B1: Not enough or no green hydrogen	not enough capacity $\sim$ Ber(0.3)	$\{0, 1\}$
C1: Pressure of hydrogen in the compressor	wrong pressure $\sim$ Ber(0.0306)	$\{0, 1\}$
NC1: Time of mechanic who fixes issues with pressure of hydrogen in the compressor	time $\sim F_{NC1}$	$[0, \infty)$ hours
D1: Green hydrogen storage	$<70\%$ hydrogen stored $\sim$ Ber(θ_{D1})	$\{0, 1\}$
D2: Leakage in the storage	leakage $\sim$ Ber(θ_{D2})	$\{0, 1\}$
ND2: Time of mechanic who fixes issues with leakages	time $\sim F_{ND2}$	$[0, \infty)$ hours
D3: Sensors that measure leakage in the storage contain an error	sensor error $\sim$ Ber(θ_{D3})	$\{0, 1\}$
ND3: Time of mechanic who fixes issues with the sensors	time $\sim F_{ND3}$	$[0, \infty)$ hours
D4: Using other types of hydrogen	other types of hydrogen $\sim$ Ber(θ_{D4})	$\{0, 1\}$
E1: Pressure of hydrogen in the transmission pipeline system	wrong pressure $\sim$ Ber(θ_{E1})	$\{0, 1\}$
NE1: Time of mechanic who fixes issues with pressure of hydrogen	time $\sim F_{NE1}$	$[0, \infty)$ hours
E2: Hydrogen leakage in the transmission pipeline system	leakage $\sim$ Ber(θ_{E2})	$\{0, 1\}$
NE2: Time of mechanic who fixes issues with leakages	time $\sim F_{NE2}$	$[0, \infty)$ hours
F1: There arises a problem in mixing hydrogen with the odorant	problem $\sim$ Ber(θ_{F1})	$\{0, 1\}$
NF1: Time of mechanic who fixes issues with mixing of the odorant	time $\sim F_{NF1}$	$[0, \infty)$ hours
F2: Pressure of hydrogen at the city gate station	wrong pressure $\sim$ Ber(θ_{F2})	$\{0, 1\}$
NF2: Time of mechanic who fixes issues with the pressure of hydrogen at the city gate station	time $\sim F_{NF2}$	$[0, \infty)$ hours
G1: Leakage in the distribution pipeline system	leakage $\sim$ Ber(θ_{G1})	$\{0, 1\}$
NG1: Time of mechanic who fixes issues with leakages	time $\sim F_{NG1}$	$[0, \infty)$ hours
G2: Sensors that measure leakage in the distribution pipeline system contain an error	sensor error $\sim$ Ber(θ_{G2})	$\{0, 1\}$
NG2: Time of mechanic who fixes issues with the sensors	time $\sim F_{NG2}$	$[0, \infty)$ hours
G3: Pressure of hydrogen in the pipeline system at street level	wrong pressure $\sim$ Ber(θ_{G3})	$\{0, 1\}$
NG3: Time of mechanic who fixes issues with the pressure of hydrogen in the pipeline system at street level	time $\sim F_{NG3}$	$[0, \infty)$ hours
H1: Hydrogen pressure at the buildings	wrong pressure $\sim$ Ber(θ_{H1})	$\{0, 1\}$
NH1: Time of mechanic who fixes issues with the pressure of hydrogen in the buildings	time $\sim F_{NH1}$	$[0, \infty)$ hours
H2: Lack of hydrogen in the buildings, in probability	lack of hydrogen $\sim F_{H2}$	$[0, 1]$
H3: Lack of hydrogen in the buildings, in time	shortage duration $\sim F_{H3}$	$[0, \infty)$ minutes

Table A.1: Introducing random variables to the events that are considered in each component of the hydrogen supply system.

Appendix B

Components of the smart gas network

In this appendix the components of the smart gas network are listed.

1. **Monitor gas network**

   Sensors measure vibration, shredding load, gas leakage, etc. around the gas pipe 24 hours a day;

2. **Smart gas meter**

   Gas meter measures gas consumption and makes it digitally available;

3. **Measuring in stations**

   Remote measurement of inlet and outlet pressure, gas quantity and gas temperature;

4. **Gas distribution**

   Measuring sensors and computer models predict the distribution and mixing of the gas flows;

5. **Dynamic pressure management**

   Control of the required gas pressure depending on the seasonal demand and supply of gas;

6. **Gas receiving station**

   Real-time data from GTS (Gasunie Transport Services) of the outlet pressure, gas quantity, gas temperature, and gas quality;

7. **Monitor gas quality**

   The gas quality of imported green gas is measured and monitored 24 hours a day;

8. **Station diagnostics**

   Periodic diagnosis of the correct operation of the control system;

9. **Cathodic protection**

   Remote diagnosis and monitoring of the plastic;

10. **Gas for transportation**

    Filling stations for gas or fuel for road and water transport;

11. **Storage**

    Storage of the produced excess capacity of green gas;

12. **Energy house in the district**

    Co-generation and/or heat pump on natural gas for heat and electricity;

13. **Inspection robot**

    Internal inspection of gas pipes;

14. **Satellite surveillance**

    Measuring land settings at street and neighborhood level.

Appendix C

Company values and business model of Stedin

Below a table is given about the company values which are used by Stedin to form a basis for the risk analysis regarding the supply in electricity and natural gas grids. In addition, the table also gives information about the business model from Stedin in 2015, i.e. the risk levels for the corresponding company values are given.

		Very small	Small	Effectiveness Mediocre	Big	Very big
Safety	Injury	Almost injury	Minor injury	Moderate injury	Serious injury	Dead or permanent disability
Quality	N.o. VBM	$<$ 100.000 VBM E; $<$ 4.000 VBM G	100.000 – 1.000.000 VBM E; 4.000 – 40.000 VBM G	1.000.000 – 10.000.000 VBM E; 40.000 – 400.000 VBM G	10.000.000 – 100.000.000 VBM E; 400.000 – 4.000.000 VBM G	$\geq$ 100.000.000 VBM E; $\geq$ 4.000.000 VBM G
	Deterioration CAIDI	$<$ 0.03 minutes	0.03 – 0.3 minutes	0.3 – 3 minutes	3 – 30 minutes	$\geq$ 30 minutes
	Unavailability of (measurable) data	$<$ 0.01%	0.01 – 0.1%	0.1 – 1%	1 – 10%	10 – 100%
Financial performance	Damage (physical and financial)	$<$ 10.000 euro	10.000 – 100.000 euro	100.000 – 1.000.000 euro	1.000.000 – 10.000.000 euro	$\geq$ 10.000.000 euro
Laws and regulations	Findings of regulator	Questions from a supervisor	Possible finding by a regulator	Findings by a regulator	Finding that there is a threat of a sanction by the regulator	Severe sanction from a regulator
Customer and stakeholder	Worst served customer	2 interruptions per year	3 interruptions per year	4 interruptions per year	5 interruptions per year	$\geq$ 6 interruptions per year
	Commotion	Handling of uncontrollable event within Stedin	Local handling of uncontrollable event	Regional treatment of uncontrollable event	National and/or political handling of an uncontrollable event	International handling of uncontrollable event
	Social damage	$<$ 10.000 euro	10.000 – 100.000 euro	100.000 – 1.000.000 euro	1.000.000 – 10.000.000 euro	$\geq$ 10.000.000 euro
	Gas evacuation hours	$<$ 10 hours	10 – 100 hours	100 – 1.000 hours	1.000 – 10.000 hours	$\geq$ 10.000 hours
Durability	Emission CO_2	$<$ 500 ton	500 – 5.000 ton	5.000 – 50.000 ton	50.000 – 500.000 ton	$\geq$ 500.000 ton
	N.o. customers that cannot participate in the energy transition in time	$<$ 100 customers	100 – 1.000 customers	1.000 – 10.000 customers	10.000 – 100.000 customers	$\geq$ 100.000 customers
Unlikely, has occurred in industry	Effect of $<$ 0.01 per year	Low	Low	Low	Mediocre	High
Possible, has occurred in Stedin	Effect of 0.01 to 0.1 per year	Low	Low	Mediocre	High	Severely high
Probably, has occurred multiple times in Stedin	Effect of 0.1 to 1 per year	Low	Mediocre	High	Severely high	Extra high
Annually, occurs once/several times in a year in Stedin	Effect of 1 to 10 per year	Mediocre	High	Severely high	Extra high	Extra high
Monthly, occurs at least once in a month in Stedin	Effect of $>$ 10 per year	High	Severely high	Extra high	Extra high	Extra high

Table C.1: Part I (grey): Company values, Part II (cyan): the Stedin business model 2015. Risk levels: from Low to Extra high. Acceptance boundary: Low: do not fix; Mediocre, High, Severely high: Risk-reduction per euro; Extra High: Fix it immediately [53].

Appendix D

Experts' results

Below a range graph of each question is given. The performance of each expert and the decision makers EWDM and PWDM is given per calibration question and question of interest. 'Item name: Q1' up to 'Item name: Q11' are the results of the calibration questions. Next the questions of interest follow.

```
                          Range graph of input data
Item no.:   1 Item name: Q1 Scale: UNI
Experts
  1 [-*-----]
  2         [---------*------------------]
  3                            [---------*------------------------------------]
EWDM [=================*=================================================]
PWDM        [========*===================]
Real:::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::
                                 16
    0,5                                                                     40

Item no.:   2 Item name: Q2 Scale: UNI
Experts
  1         [---------------*----------------]
  2 [-------*---------------]
  3         [------------------------*----------------------------------------]
EWDM [===================*===============================================]
PWDM [=======*================]
Real::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
           1,98
     1                                                                      10

Item no.:   3 Item name: Q3 Scale: UNI
Experts
  1            [------------*-------------]
  2 [-------------*-----------------------------------------------------------]
```

```
  3   [---*-------]
EWDM [===========*====================================================]
PWDM [=============*===========================================================]
Real::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
          4,6
    0,5                                                                      50

Item no.:   5 Item name: Q5 Scale: UNI
Experts
  1 [--*-----------------]
  2 [-----*--------------------------------------------------------------------]
  3                                              [-------*------]
EWDM [==================*===============================================]
PWDM [=====*====================================================================]
Real:::::::::::::::::::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::
                                            5,49
    0,1                                                                      10

Item no.:   1 Item name: Q1 Scale: UNI
Experts
  4               [--------------*-------]
  5        [----------*----------]
  6                         [-*-]
  7 [------------------------------------*-------------------------------------]
  8            [-----------------*-------]
  9                         [--------*----------]
EWDM       [===================*===================================]
PWDM     [=============*=======================================]
Real:::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                  34,1
    30                                                                       50

Item no.:   2 Item name: Q2 Scale: UNI
Experts
  4         [-----------*--------]
  5               [-----------*------------------------------------------------]
  6                             [--*--]
  7                           [-----------*-----------]
  8                     [--*-----]
  9                     [-------*---------------------]
EWDM           [================*=================================]
PWDM               [=============*=============================================]
Real#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     75
    75                                                                      200
```

```
Item no.:   3 Item name: Q3 Scale: UNI
Experts
  4 [-*-]
  5     [---*-----------------------------------------------------------------]
  6 [-------*----]
  7               [---*---]
  8        [*]
  9       [-*]
EWDM [======*============================================]
PWDM    [=========*==========================================================]
Real#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     26
    26                                                                     400

Item no.:   4 Item name: Q4 Scale: UNI
Experts
  4                 [--------*-------]
  5                 [----------------*----------------]
  6 [--------------------------------*----------------------------------------]
  7                          [-------*-------]
  8                              [---*---]
  9                          [---*---]
EWDM        [=====================*===============================]
PWDM                [================*===============]
Real:::::::::::::::::::::::::::::::::::::::::#:::::::::::::::::::::::::::::::::
                                            0,006
    0,001                                                                 0,01


Item no.:   1 Item name: Q5 Scale: UNI
Experts
  1                      [----------------*-----------------------------------]
  2          [-------------------------------*----------------]
  3                      [-------------------*----------------]
  4          [----------------*--------------]
  5          [----*----]
  6 [------*------]
  7          [-----------*-----------]
  8               [-*-------]
  9               [-*---------]
PWDM            [====*==============================]
EWDM   [=================*======================================]
Real::::::::::::::::::::::::#::::::::::::::::::::::::::::::::::::::::::::::::::
                            11
     1                                                                       32
```

```
Item no.:   2 Item name: Q6 Scale: LOG
Experts
  1                                      [------*--]
  2                                  [---------*---------]
  3          [-------------*--]
  4                            [------*--]
  5                                  [*--]
  6                                                                           []
  7                        [---------*--]
  8                       [---------*---------]
  9                                      [----*-]
PWDM                       [===========*===============]
EWDM               [=====================*=====================================]
Real#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     5,4E-007
    5,4E-007                                                                12

Item no.:   3 Item name: Q7 Scale: LOG
Experts
  1                                     [--*---]
  2               [----------*----------]
  3 [--*--]
  4                          [----------*--]
  5                           [---*-----]
  6                                                                    [------*]
  7               [----------*--]
  8   []
  9                                                                    [----*-]
PWDM  [*====================================]
EWDM [=============================*==========================================]
Real::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
           4,1E-005
    5E-006                                                                  30

Item no.:   4 Item name: Q8 Scale: LOG
Experts
  1                      [--------------------*----------]
  2                                                       [----------*---------]
  3                                                    [--*--]
  4                                                    [--*----]
  5                                                               [--*-----]
  6 [-----------------*--------------]
  7                                            [----------*--]
  8                      [----------*--------------------]
  9                                  [------*]
PWDM                     [===========*=================================]
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EWDM         [=========================================*==================]
Real::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::
                   5,5E-007
    1E-008                                                                 0,1

Item no.:   5 Item name: Q9 Scale: UNI
Experts
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  6    [---*------------------------------------------------------------------]
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  8 *]
  9 |
PWDM *]
EWDM *==========================================]
Real#:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
     34
     1                                                                   1E005

Item no.:   6 Item name: Q10 Scale: UNI
Experts
  1  [-]
  2 [--*---------]
  3       [------*---------------]
  4 []
  5           [--*------------------------------------------------------------]
  6     [--------*--]
  7 *]
  8 [------------*------------------------------------------------------------]
  9 [*-]
PWDM [===========*=============================================================]
EWDM [==*=======================================================]
Real:::#::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
        3
     1                                                                      50

Item no.:   7 Item name: Q11 Scale: LOG
Experts
  1                                                          [------*-]
  2    [---------*-------------------]
  3                                                                 [--*---]
  4                                                                 [------*--]
  5 [------------*------]
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  6                                                    [--*----]
  7                                  [-------*--]
  8 [---------*--]
  9                                                                   [--*-]
PWDM [=========*=============================================]
EWDM   [==================================================*==================]
Real::::::::::::::::::::#:::::::::::::::::::::::::::::::::::::::::::::::::::::::
                      5E-005
    5E-007                                                                   10

Item no.:   8 Item name: Q12 Scale: UNI
Experts
  1    [--*]
  2   [--*------------------------------------------------]
  3 [*----------]
  4             [-----------*------------]
  5       [-------------------------------------------------------*-----------]
  6             [------------------*-----------]
  7  [----*-]
  8       [-----*-----]
  9  [-*--]
PWDM   [========*====================]
EWDM [=======*==========================================================]
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    0,001                                                                   0,6

Item no.:   9 Item name: Q13 Scale: UNI
Experts
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PWDM *]
EWDM *========================================]
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    0,1                                                                   1E007

Item no.:  10 Item name: Q14 Scale: UNI
Experts
  1 |
  2 [*]
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  3                     [--------------------*--------------------------------]
  4                         [----------------*------------------------]
  5                                                           [---*---]
  6                 [-------*----------------]
  7     [---------------*--------------------]
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  9     [---------------*---]
PWDM [==================================================*=============]
EWDM [==========================*======================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                 0,9

Item no.:  11 Item name: Q15 Scale: UNI
Experts
  1       [------*------]
  2 *---]
  3   [-*-------------------]
  4     [-------------------*-------------------]
  5 *-]
  6          [--------------*----]
  7                         [------------------------*------------------------]
  8                         [------------------------*------------------------]
  9 [-*-]
PWDM [=============================================*==========================]
EWDM [============*=====================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,0001                                                                0,15

Item no.:  12 Item name: Q16 Scale: UNI
Experts
  1 |
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PWDM [=================================*=======================================]
EWDM *=======================================================]
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    0,01                                                                 2E005

Item no.:  13 Item name: Q17 Scale: UNI
Experts
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  9    [----------------------------------*------------------------------------]
PWDM [=================================*========================================]
EWDM *========================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,01                                                                   2E005

Item no.:  14 Item name: Q18 Scale: UNI
Experts
  1 *------]
  2      [*-------------]
  3 |
  4        [------------------------------*------------------------------------]
  5   [*----------------]
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  9 [--*---]
PWDM *===============]
EWDM [=*====================================================]
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    1E-007                                                                  0,1

Item no.:  15 Item name: Q19 Scale: UNI
Experts
  1 *------]
  2 [------*-------------------------------------------------------------------]
  3 *------]
  4 [------*------]
  5   [*----------------]
  6  [-*]
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  8 *------]
  9 [--*---]
PWDM [*=============================]
EWDM [=*===========================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-005                                                                  0,1
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Item no.:  16 Item name: Q20 Scale: UNI
Experts
  1   [----*---]
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PWDM *========]
EWDM [*=================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-006                                                                0,822

Item no.:  17 Item name: Q21 Scale: UNI
Experts
  1  [-*-]
  2    [-----*------------------------------------------]
  3                   [------------------*----------------------]
  4        [---------------------*------]
  5 *]
  6    [---*---]
  7                     [-------------------------------------*-------------]
  8
  9 []
PWDM [=====*===============================================]
EWDM [======*===========================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,005                                                                  0,99

Item no.:  18 Item name: Q22 Scale: UNI
Experts
  1 [-*]
  2 *---]
  3    [---*-------]
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  6 [*]
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PWDM [*===========================]
EWDM [=*==============================================================]
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    0,0005                                                                 0,99

Item no.:  19 Item name: Q23 Scale: UNI
Experts
  1                                               [----*--------------]
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  4    [--------------*------------------]
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  6    [---*---]
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  9  [-*---]
PWDM [=*=========================================================]
EWDM [====*=========================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-006                                                                  0,2

Item no.:  20 Item name: Q24 Scale: UNI
Experts
  1   [-------*-----]
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  3 *------]
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  9    [---*-------]
PWDM *========================]
EWDM [*======================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-017                                                                  0,1

Item no.:  21 Item name: Q25 Scale: UNI
Experts
  1                         [------------------------*------------------------]
  2 [--------*-----------------------------------]
  3                       [----------------------*----------------------]
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PWDM [=======*=========================================================]
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EWDM [*===============================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,0001                                                                0,82

Item no.:  22 Item name: Q26 Scale: UNI
Experts
  1 [-*]
  2  [------------*-----------------------------------------------------------]
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PWDM [=====*================================================================]
EWDM *===============================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-006                                                                 0,5

Item no.:  23 Item name: Q27 Scale: UNI
Experts
  1          [---------------------------------------*------------------------]
  2 *------------------------------------------------]
  3  [---*------------]
  4 [*]
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PWDM [*================================================================]
EWDM *============================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    1E-006                                                                0,41

Item no.:  24 Item name: Q28 Scale: UNI
Experts
  1 *]
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  6 *---------------------------------]
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PWDM *================]
EWDM *================================================]
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    0,001389                                                               720

Item no.:  25 Item name: Q29 Scale: UNI
Experts
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  2 *-------------------------------------------------------------------------]
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PWDM *==========================]
EWDM *========================================]
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    0,25                                                                 1E004

Item no.:  26 Item name: Q30 Scale: UNI
Experts
  1 |
  2 *]
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  4    [---*-----]
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  7 *-------------------------------------------------------------------------]
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  9 |
PWDM *===]
EWDM *=========================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,001389                                                              1008

Item no.:  27 Item name: Q31 Scale: UNI
Experts
  1  [-*-]
  2  [*-------]
  3  [--------------------*---------------------------------------------------]
  4  [-*-]
  5  [---*----]
  6  [-*---]
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  7 [---------*----------]
  8 *]
  9 *]
PWDM *========]
EWDM [==*=============================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,001389                                                               168

Item no.:  28 Item name: Q32 Scale: UNI
Experts
  1                      [----------*-----------------------------------------]
  2      [--*-----------------------]
  3  [---*----]
  4   [--*----]
  5                 [---------------*-------------------------------]
  6      [----*----------]
  7 [-------------------------------*-------------------------------]
  8     [*--------------------------]
  9 *]
PWDM [====*===============================]
EWDM [========*===================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,001389                                                                56

Item no.:  29 Item name: Q33 Scale: UNI
Experts
  1                   [------------------*------------------------------------]
  2 [---*-]
  3     [-------------*------------------]
  4                   [------------------*------------------]
  5     [----*--------]
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  9 [*--]
PWDM  [===============*=====================================]
EWDM [==============*===========================================]
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    0,0833                                                                  16

Item no.:  30 Item name: Q34 Scale: UNI
Experts
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PWDM *=]
EWDM *====================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,001389                                                               2000

Item no.:  31 Item name: Q35 Scale: UNI
Experts
  1         [---------*------------------]
  2     [----------------------*----------------------------]
  3     [---*---------]
  4     [-*-]
  5  [------*---------]
  6                   [------------------*------------------------------------]
  7  [------*---------]
  8       [--------------------*----------------------------]
  9 *]
PWDM  [========================*============================]
EWDM [===========*=============================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,25                                                                     32

Item no.:  32 Item name: Q36 Scale: UNI
Experts
  1 |
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  4 [*-]
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  7 *-------------------------------------------------------------------------]
  8 |
  9 |
PWDM *=]
EWDM *========================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,001389                                                               1008

Item no.:  33 Item name: Q37 Scale: UNI
Experts
  1                   [------------------*------------------------------------]
  2 [---*----]
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  3     [--------*---------]
  4     [-*----]
  5   [-*----]
  6   [-*----]
  7   [------*--------]
  8       [---------------------*---------------------------]
  9 [-*---]
PWDM [========================*=============================]
EWDM [======*================================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,0833                                                                  32

Item no.:  34 Item name: Q38 Scale: UNI
Experts
  1                  [------------------*-------------------------------------]
  2    [----*------------------]
  3         [------------------*------------------]
  4         [--------*------------------]
  5                  [------------------*------------------]
  6      [--*-]
  7    [-------------*------------------]
  8         [--------*-------------------------------------]
  9 [*------]
PWDM    [============*======================================]
EWDM [================*=========================================]
    ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    0,25                                                                    16
```

Appendix E

Elicitation Protocol

In this project we use an elicitation protocol that consists of four parts. In the first part a description of the pilot is given to the experts. The second part is based on the paper 'Procedures Guide for Structural Expert Judgement in Accident Consequence Modelling'. The third part describes the assumptions that are made in order to answer the questions. The last part was given in a word document to the experts where all the questions are shown. For the sake of completeness, the questions are also given in this appendix.

E.1 Pilot description

In this thesis we are considering a pilot from Stedin, which concerns providing the city Stad aan 't Haringvliet with hydrogen instead of natural gas for the same heating purposes. Switching from natural gas to hydrogen involves numerous sources of uncertainty, which need to be appropriately quantified for an accurate overall risk picture. Therefore the scope of this thesis is quantifying security risks of supplying with 100% hydrogen in built-environment.

In Figure E.1 the project of Stedin is given in the form of events, which we discuss now. In order to produce hydrogen by electrolysis, green electricity is needed. Green electricity can be obtained with the help of wind turbines and solar panels. Then the process of electrolysis can start where water molecules are split into hydrogen and oxygen gas. Excessive amount of hydrogen can be stored in tanks at pressures of 80 bar, which is first compressed by the compressor from 30-35 bar. Next, the produced hydrogen is transferred in a pipeline system that operates at 80 bar to 40 bar in the Island of Goeree Overflakkee. A pipeline from this island brings the required hydrogen to Stad aan 't Haringvliet. This pipeline needs to pass through the city gate station first, where the pressure is reduced to 8 bar and then to 100 millibar on street level. All the other pipeline networks which are connected with Stad aan 't Haringvliet are disconnected. After the pipeline with hydrogen passes through the city gate station, the distribution of hydrogen through the pipeline system starts. The hydrogen flows through the system to the households.

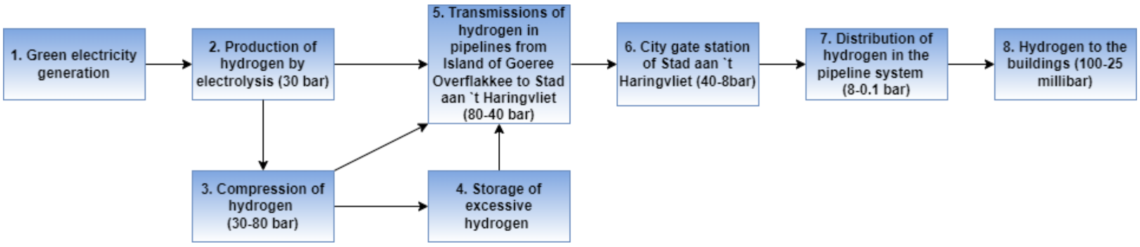

Figure E.1: System for hydrogen supply.

A more systematic diagram can be given of this system for hydrogen supply, which gives insight into the problems that can occur and the respective consequences, see Figure E.2. Each green component, which is marked with a number and sometimes followed by an letter 'A' corresponds with a component in the system of hydrogen supply, see Figure E.1. In order to obtain a sufficient amount of hydrogen in the buildings (number 7), there should not occur any problems in the processes denoted by number 4A, 5A, and 6A. When there is no green electricity production or the process of electrolysis is disturbed for some time, it results in not producing green hydrogen in that time period. We can solve this problem by using hydrogen from the storage or even other types of hydrogen from tube trailers. When problems occur with the compression of green hydrogen, the produced green hydrogen cannot be used to supply the building from hydrogen. In order to still obtain a sufficient amount of hydrogen in the buildings, green hydrogen from the storage can be used in this time period, if there is enough green hydrogen stored. If there is not enough green hydrogen stored, other types of hydrogen can be used to supply the buildings of hydrogen.

E.1.1 Assumptions

In this project some assumptions have been made for the event sequence diagram given in Figure E.2.

1. In the influence diagram, we have the following steps for hydrogen production/supply before entering the transmission network:

   i) using green electricity from the network and electrolyser to produce hydrogen;

   ii) if no green electricity is available, we use hydrogen from the storage;

   iii) if there is not enough hydrogen in the storage or there is an issue with the storage, then we buy hydrogen from external sources (e.g, tube trailers);

   iv) hydrogen enters the transmission grid.

   This means that we always have hydrogen entering the transmission grid (as shown in the diagram). This implies that any issues related to the electrolyser or compressor will not influence hydrogen supply at the buildings and we do not need to include them in the risk model;

2. The first component in Figure E.2 is not only about pure green electricity, i.e. electricity produced by renewable resources, but also electricity that has a green certificate;

3. At the start, the electrolysis will be connected to the electricity grid and not directly to a sun or wind farm. Here we consider all the energy on the Island of Goeree Overflakkee and this one is about 70% sustainable per year. It is expected that more sustainable capacity will be added to the island in the near future, so that the share will increase more. The Goeree Overflakkee area produces much more sustainable energy (sun and wind) than it consumes. In this project we consider therefore wind turbines that produce hydrogen directly and electrolyser linked to the E-grid (or directly linked to a solar park);

4. Enough green electricity means that we have an amount of green electricity such that we do not have to use hydrogen from the storage;

5. Enough green hydrogen capacity means that we have an amount of green hydrogen such that we do not have to use other types of hydrogen. Other types of hydrogen are e.g. black hydrogen, grey hydrogen, blue hydrogen, yellow hydrogen etc. Hydrogen of these types are not produced using electricity generated from renewables. In emergency situations we are going to tap another power. For example, hydrogen that comes from industry. This happens about once every 10 years;

6. An average household consumes 1.300m^3 natural gas per year, where roughly 80% of the gas is used for heating up the home, 18% for hot water and 2% for cooking (furnace). Together with the fact that around 600 houses in Stad aan 't Haringvliet consume 780.000m^3 natural gas per year. This means that we need around 2.340.000m^3 of hydrogen for the same amount of energy. Based on the estimates from a literature, we assume that 1kg (or 11.1m^3) of hydrogen requires 54.3 kWh of electricity to produce it via electrolysis. This means that the electricity demand to generate the hydrogen demand equals

$$\frac{2.340.000}{11.1} \times 54.3 \text{ GWh} \approx 11.5 \text{ GWh}$$

approximately per year;

7. Problems with compressing hydrogen means that the compressor machine fails to compress the hydrogen at 30-50 bar to 80 bar;

8. The hydrogen storage should contain at least 70% of the storage capacity. Any percentage less than 70% corresponds the event of not having enough hydrogen stored;

9. A pressure failure means that the hydrogen does not have the required pressure value in that stage of the system, but a value below the required threshold. (The pressure value of hydrogen can only drop after compressing hydrogen);

10. A hydrogen leakage in the pipeline system can occur when there are holes in the pipeline. Both large holes (i.e. $\frac{1}{3}$ diameter of the pipeline) and holes smaller than < 5 mm diameter cause leakage. Furthermore, a leakage can also be caused by rupture and brittle material of the pipeline;

11. The pipelines in which hydrogen is transported consist of steel pipelines with a diameter of 200mm. In the distribution part where there is high pressure, steel and PE is used for the pipelines. PVC, PE, and copper are used for the low pressure in the distribution section. In the households we are dealing with pipes made of steel. The diameters vary from 15 to 200mm;

12. It is possible that when hydrogen is mixed with the odorant, that this does not go well. A small amount of odorant can be added in proportion to the hydrogen volume. When a leak occurs, the odorant is barely smelled and this can have problematic consequences;

13. A lack of hydrogen in the buildings means that the heating purposes in the buildings are not achieved. The compressing stage is thus not working.

E.2 Protocol

Structured expert judgment is an accepted tool in risk analysis for supplementing data shortfalls, quantifying uncertainty and building rational consensus. Switching from natural gas to hydrogen involves numerous sources of uncertainty, which needs to be appropriately quantified for an accurate overall risk picture. With this respect, the lack of (appropriate) data makes the endeavour even more challenging. In these circumstances, expert opinion remains the only reliable knowledge source to quantify uncertainties. A panel of experts quantify uncertainty with regard to variables of interest and calibration variables from the subject area. Elicitation is done by specifying percentiles of uncertain quantities, as illustrated below.

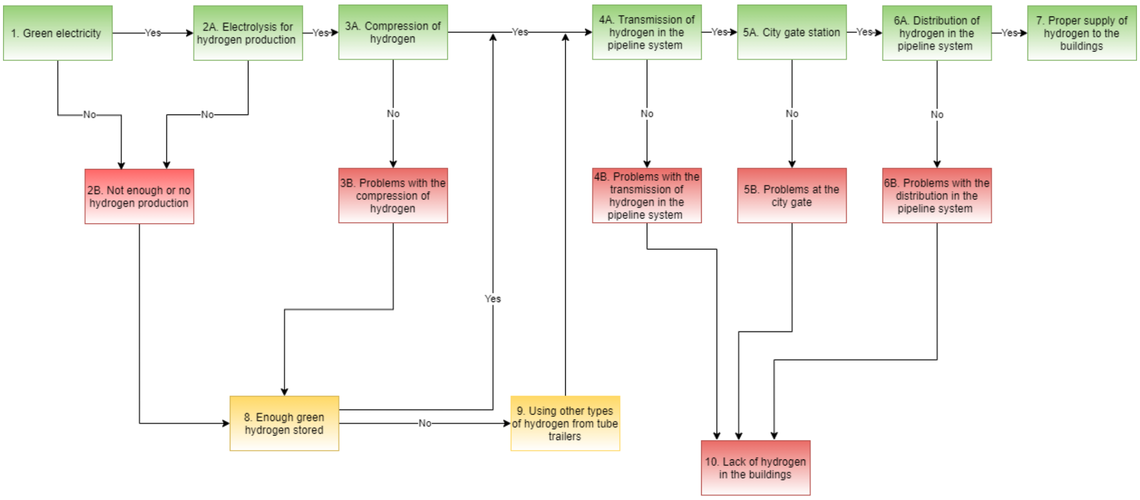

Figure E.2: Systematic event influence diagram for hydrogen supply.

Elicitation Format:
You are presented with an uncertain quantity:
"What is the gas consumption per hour in Stad aan 't Haringvliet, in m^3/h, at temperature -12 °C"
5% : ... 50% : ... 95% : ...

You are asked to quantify your uncertainty by specifying percentiles of your subjective uncertainty:

- The 50%-tile is that number for which you judge the chance half that the true value is above or below.
- The 5%-tile is that number for which the chance that the true value is below 0.05 and the chance that the true value is above 0.95.
- The 95% -tile is that number for which the chance that the true value is below 0.95, and the chance that the true value is above 0.05.

We always have 5%-tile $<$ 50%-tile $<$ 95%-tile.

Suppose you respond as: 5% : 2000, 50% : 2500, 95% : 3000. Then this means that, in expert opinion, the true value is equally likely to be above or below 2500; there is a 90% chance that it lies between 2000 en 3000.

A good probability assessor is one whose assessments capture the true values with the long run correct relative frequencies (statistically accurate), with distributions that are as narrow as possible (informative). Informativeness is gauged by 'how far apart the percentiles are' relative to an appropriate background.

In gauging overall performance, statistical accuracy is more important than informativeness. Non-informative but statistically accurate assessments are useful, as they sensitize us to how large the uncertainties may be; highly informative but statistically very inaccurate assessments are not useful. Do not shy away from wide distributions if that reflects your real uncertainty.

If you have little knowledge about an item, this fact by itself does not disqualify you as an uncertainty assessor. Knowing little means that your percentiles should be 'far apart'. If other experts are more informative, without sacrificing accuracy, then they will exert more influence on the decision maker. But if there are no statistically accurate experts with more informative assessments, then the uninformative assessments accurately depict the uncertainty. That in itself is very important information.

E.2.1 Set 1: Calibration questions

1. What percentage of Europe's electricity is currently given by wind energy, according to Wind Europe?

2. According to Wind Europe, Europe installed 14.7 GW of new wind capacity in 2020. The Netherlands installed the most wind power capacity. How much was that (in GW)?

3. Global Market Outlook for solar power 2021-2025 is a report by Solar Power Europe. What is the total volume (in GW) the Dutch solar market is expected to reach by 2025?

4. What was the percentage of renewables from the Netherlands' total energy mix in 2020?

5. The study by Khan, Al-Shankiti and Idriss (2021) reports a 28% efficiency of green hydrogen production using solar energy, based on an analysis designed for a plant in Saudi Arabia, which is assumed to operate around 9 hours per day without grid support. What is the hydrogen production rate (ton per h)?

6. A study by Casamirra, Catiglia and Lombardo (2009) investigated the safety of a hydrogen refuelling station by quantifying the occurrence frequency of certain accidental scenarios. A hydrogen power park, to be realized in California was used as the reference plant. What is the frequency of the event 'storage vessel overpressure', resulted from the analysis for the plant working during one year without a maintenance?

7. A 2008 report prepared by the 'Health and Safety Laboratory' in UK details the failure rates for underground gas storage. Data on eight European companies was collected, that owned 42 sites in total, which corresponds to 845 wells. Operating experience was estimated for these 42 sites and calculated to be 100,155 well years. According to this report, what was the rate for well failure, in salt caverns in Europe, per well year?

An RIVM report from 2011, regarding on-site natural gas onshore, above ground and high-pressured piping reports scenarios and failure frequencies.

8. Data on Dutch natural gas industry, supplied by Gasunie, NAM, TAQA and Vermilion was used to compute failure frequencies. What was the average failure frequency for flange connections based on Dutch industry data?

9. According to the same report, how many incidents with flange leakages have been reported by Gasunie in the previous 12 years?

The NREL report 'Blending hydrogen into natural gas pipeline network: a review of key issues', from 2013 investigated key issues related to blending hydrogen into natural gas pipeline network.

10. Leakage measurements for steel and ductile iron gas distribution systems (including seals and joints) suggest an increase in leakage volume of hydrogen when compared to natural gas. What is the factor by which the volume leakage rate for hydrogen is higher than that for natural gas?

11. The report mentions a calculation for the Dutch pipeline system from 2003, which considers a 17% hydrogen blend. What is the predicted gas leakage rate?

E.2.2 Set 2: Calibration Question

1. Natural gas consumption in The Netherlands was 36.6 billion cubic meters (bcm) in 2015. What was the consumption (in bcm) in 2020?

2. Stedin aims to improve supply (e.g., natural gas) security by taking initiatives aimed at reducing downtime and at preventing interruptions. According to its 2020 annual report, the average duration of interruption in gas supply in 2018was 122 minutes. What was the average duration of interruption in gas supply in 2020, in minutes?

3. According to the same annual report of question 2, the annual average downtime in gas supply in 2018 was 69 seconds.What was the annual average downtime in gas supply, in seconds, in 2020?

4. Stedin also reports the System Average Interruption Frequency Index (SAIFI), which is defined as the average numberof unforeseen interruptions with which customers are faced on an annual basis. In 2019, this index was 0.005. What wasthe index in 2020?

5. What was the percentage of renewables from the Netherlands' total energy mix in 2020?

6. A study by Casamirra, Catiglia and Lombardo (2009) investigated the safety of a hydrogen refuelling station by quantifying the occurrence frequency of certain accidental scenarios. A hydrogen power park, to be realized in California was used as the reference plant. What is the frequency of the event 'storage vessel overpressure', resulted from the analysis for the plant working during one year without a maintenance?

7. A 2008 report prepared by the 'Health and Safety Laboratory' in UK details the failure rates for underground gas storage. Data on eight European companies was collected, that owned 42 sites in total, which corresponds to 845 wells. Operating experience was estimated for these 42 sites and calculated to be 100,155 well years. According to this report, what was the rate for well failure, in salt caverns in Europe, per well year?

An RIVM report from 2011, regarding on-site natural gas onshore, above ground and high-pressured piping reports scenarios and failure frequencies.

8. Data on Dutch natural gas industry, supplied by Gasunie, NAM, TAQA and Vermilion was used to compute failure frequencies. What was the average failure frequency for flange connections based on Dutch industry data?

9. According to the same report, how many incidents with flange leakages have been reported by Gasunie in the previous 12 years?

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10. Leakage measurements for steel and ductile iron gas distribution systems (including seals and joints) suggest an increase in leakage volume of hydrogen when compared to natural gas. What is the factor by which the volume leakage rate for hydrogen is higher than that for natural gas?

11. The report mentions a calculation for the Dutch pipeline system from 2003, which considers a 17% hydrogen blend. What is the predicted gas leakage rate?

E.2.3 Questions of Interest

1. How likely is it that there is not enough hydrogen in the buildings, in probability?

2. Consider the event of not having enough hydrogen in the buildings. How long do you expect this to last, in minutes?

3. How likely is it that the hydrogen storage contains less than 70% of the storage capacity, in probability?

4. How likely is it that the amount of odorant added to the hydrogen is insufficient, i.e., enough for a leakage not to be detected, in probability?

5. Consider 1,000,000 leakages incidents in the storage. How many times does the sensor that measures leakage in the storage contain an error (so the sensor does not report the leakage, or the sensor does report a leakage when it does not occur)?

6. Suppose there are 1,000,000 leakages incidents in the distribution pipeline system. How many times does the sensor that measures leakage in the distribution pipeline system contain an error (so the sensor does not report the leakage, or the sensor does report a leakage and it is not the case)?

7. How likely is it that there is a hydrogen leakage in the storage, in probability?

8. How likely is it that there is a hydrogen leakage in the transmission pipeline system, in probability?

9. How likely is it that there is a hydrogen leakage in the distribution pipeline system, in probability?

10. How likely is it that hydrogen pressure in the transmission part will be lower than 40 bar, in probability?

11. How likely is it that the hydrogen pressure in the transmission part will be lower than 8 bar, in probability?

12. How likely is it that the hydrogen pressure at the city gate station will be lower than 8 bar, in probability?

13. How likely is it that the hydrogen pressure at the city gate station will be lower than 100 millibar, in probability?

14. How likely is it that the hydrogen pressure at street level will be lower than 100 millibar, in probability?

15. How likely is it that the hydrogen pressure at street level will be lower than 25 millibar, in probability?

16. How likely is it that the hydrogen pressure in the buildings will be lower than 25 millibar, in probability?

17. Suppose the compressor machine fails to compress the hydrogen to 80 bars. How long do you expect it will take a mechanic to fix this issue, in hours?

18. Assuming there is a detected hydrogen leakage in the storage, how long will it take a mechanic to fix the issue, in hours?

19. Assume a sensor that measures leakage in the storage contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

20. Assume there is a hydrogen pressure drop in the transmission pipeline system that can lead to a lack of supply. How long do you expect it will take a mechanic to fix this issue, in hours?

21. Assuming there is a hydrogen leakage in the transmission pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

22. Assuming there arises a problem with mixing hydrogen with the odorant, how long do you expect it will take a mechanic to fix this issue, in hours?

23. Assuming there is a hydrogen pressure failure at the city gate station, how long do you expect it will take a mechanic to fix this issue, in hours?

24. Assuming there is a hydrogen leakage in the distribution pipeline system, how long do you expect it will take a mechanic to fix this issue, in hours?

25. Assume a sensor that measures leakage in the distribution pipeline system contains an error, how long do you expect it will take a mechanic to fix the issue, in hours?

26. Assuming that there is hydrogen pressure failure in the pipeline system at street level, how long do you expect it will take for mechanic to fix this issue, in hours?

27. Assuming there is a hydrogen pressure failure in the buildings, how long do you expect it will take for mechanic to fix this issue, in hours?

Appendix F

Sources for the calibration questions

Several sources were used to construct the calibration questions. In this appendix we give the true values of the calibration questions.

The first two calibration questions from the first set are constructed with the help of Wind Europe [54].

1. What percentage of Europe's electricity is currently given by wind energy, according to Wind Europe?
Answer: 16%.

2. According to Wind Europe, Europe installed 14.7 GW of new wind capacity in 2020. The Netherlands installed the most wind power capacity. How much was that (in GW)?
Answer: 1.98 GW.

The third question from set 1 and fourth/fifth questions from set 1/2 are constructed by using the report Global Market Outlook for Solar Power [55].

3. Global Market Outlook for solar power 2021-2025 is a report by Solar Power Europe. What is the total volume (in GW) the Dutch solar market is expected to reach by 2025?
Answer: 4.6 GW.

4/5. What was the percentage of renewables from the Netherlands' total energy mix in 2020?
Answer: 11%.

The fifth question from set 1 has been constructed by using data from the study 'Demonstration of green hydrogen production using solar energy at 28% efficiency and evaluation of its economic viability' [56].

5. The study by Khan, Al-Shankiti and Idriss (2021) reports a 28% **efficiency of green hydrogen production using solar energy, based on an analysis de-**

signed for a plant in Saudi Arabia, which is assumed to operate around 9 hours per day without grid support. What is the hydrogen production rate (ton per h)?
Answer: 5.49 ton per hour.

For the first question in set 2, a bar diagram about 'Natural gas consumption in the Netherlands from 2005 to 2020' in billion cubic meterwas used [57].

1. Natural gas consumption in The Netherlands was 36.6 billion cubic meters (bcm) in 2015. What was the consumption (in bcm) in 2020?
Answer: 34.1 bcm.

Question 2 and 3 from the second set are constructed by using an annual report from Stedin from 2020 [29].

2. Stedin aims to improve supply (e.g., natural gas) security by taking initiatives aimed at reducing downtime and at preventing interruptions. According to its 2020 annual report, the average duration of interruption in gas supply in 2018 was 122 minutes. What was the average duration of interruption in gas supply in 2020, in minutes?
Answer: 75 minutes.

3. According to the same annual report of question 2, the annual average downtime in gas supply in 2018 was 69 seconds.What was the annual average downtime in gas supply, in seconds, in 2020?
Answer: 26 seconds.

An extract annual report from Stedin from 2020 has been used to construct the fourth question in set 2, see [58].

4. Stedin also reports the System Average Interruption Frequency Index (SAIFI), which is defined as the average number of unforeseen interruptions with which customers are faced on an annual basis. In 2019, this index was 0.005. What was the index in 2020?
Answer: 0.006

The sixth question has been constructed by using data from the study 'Safety studies of a hydrogen refuelling station: Determination of the occurrence frequency of the accidental scenarios' [18].

6. A study by Casamirra, Catiglia and Lombardo (2009) investigated the safety of a hydrogen refuelling station by quantifying the occurrence frequency of certain accidental scenarios. A hydrogen power park, to be realized in California was used as the reference plant. What is the frequency of the event 'storage vessel over-pressure', resulted from the analysis for the plant working during one year without a maintenance?
Answer: 5.4×10^{-7}.

The seventh question has been constructed by using data from the report 'Failure rates for underground gas storage', see [59].

7. A 2008 report prepared by the 'Health and Safety Laboratory' in UK details the failure rates for underground gas storage. Data on eight European companies was collected, that owned 42 sites in total, which corresponds to 845 wells. Operating experience was estimated for these 42 sites and calculated to be 100,155 well years. According to this report, what was the rate for well failure, in salt caverns in Europe, per well year?
Answer: 4.1×10^{-5}.

An RIVM report from 2011, regarding on-site natural gas onshore, above ground and high-pressured piping reports scenarios and failure frequencies [11]. Question 8 and 9 are about this report.

8. Data on Dutch natural gas industry, supplied by Gasunie, NAM, TAQA and Vermilion was used to compute failure frequencies. What was the average failure frequency for flange connections based on Dutch industry data?
Answer: 5.5×10^{-7}.

9. According to the same report, how many incidents with flange leakages have been reported by Gasunie in the previous 12 years?
Answer: 34.

The NREL report 'Blending hydrogen into natural gas pipeline network: a review of key issues', from 2013 investigated key issues related to blending hydrogen into natural gas pipeline network [60]. Question 10 and 11 are about this report.

10. Leakage measurements for steel and ductile iron gas distribution systems (including seals and joints) suggest an increase in leakage volume of hydrogen when compared to natural gas. What is the factor by which the volume leakage rate for hydrogen is higher than that for natural gas?
Answer: 3.

11. The report mentions a calculation for the Dutch pipeline system from 2003, which considers a 17% hydrogen blend. What is the predicted gas leakage rate?
Answer: $5 \times 10^{-5}\%$.

Appendix G

Distribution of the decision makers

In this appendix we show for every question of interests its distribution according to some decision makers. We start by considering the decision makers where 11 calibration questions were taken into account and that the expert that left a calibration question open, has an assessment in the 0%- and 5%- quantile. The case were this expert has another assessments or were we leave out this calibration questions, will lead to similar distributions since its effect is not easily seen in the graphs. Therefore we leave the graphs for those cases out in thesis. Next, we show for every question of interests its distribution according to the decision makers where in the analysis 7 calibration question were taken into account. These 7 calibration questions were included in the first set as well as in the second set of the calibration questions.

There are some practical issues that needs to be discussed here. Excalibur enables to calculate the distributions of the decision makers EWDM and PWDM when some questions of interests are left open. However, for OPWDM this is not possible. Furthermore, the 100 quantile points and the corresponding values in the graphs with 11 calibrations questions taken into account are attained from the Excalibur and converted to Excel in order to construct the graphs. The graph that take 7 calibration question into account are attained from R, because it is impossible to construct the decision makers in Excalibur that are used in this graph. It is possible to construct in R 100 quantile points and the corresponding values for these decision makers. However due to practical reasons and managing the time efficiently, this is not done, which limits the graphs with 3 quantile values, namely 5, 50, and 95%- quantiles.

G.1 Distributions with 11 calibration questions taken into account

Below 27 graphs are given, each for every question of interest. In the analysis 11 calibration questions have been taken into account. Note that some questions have not been answered by all the experts. Question of Interest 5, 6, 10, 11, 12, 13, 14, 15, 16, and 17 have been answered by 8 experts instead of 9. Before considering the graphs a list is given, where a description of the decision makers in the legend is given, in order to understand the graphs.

Desicion maker	**Description**
EWDM1	Equal-Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
EWDM2	Equal-Weighted Decision Maker with 6 experts that answered the second set of the calibration questions.
PWDM1	Performance Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
PWDM2	Performance Weighted Decision Maker with 6 experts that answered the second set of the calibration questions.
OPWDM1	Optimised Performance Weighted Decision Maker with 3 experts that answered the first set of the calibration questions.
OPWDM2	Optimised Performance Weighted Decision Maker with 4 experts that answered the second set of the calibration questions and all of the questions of interest.
OPWDM3	Optimised Performance Weighted Decision Maker with 6 experts that answered the second set of the calibration questions without the questions of interest that was not answered by everyone.

G.2 Distributions with 7 calibration questions taken into account

Below 27 graphs are given, each for every question of interest. In the analysis 7 calibration questions have been taken into account. Note that some questions have not been answered by all the experts. Question of Interest 5, 6, 10, 11, 12, 13, 14, 15, 16, and 17 have been answered by 8 experts instead of 9. Before considering the graphs a list is given, where a description of the decision makers in the legend is given, in order to understand the graphs.

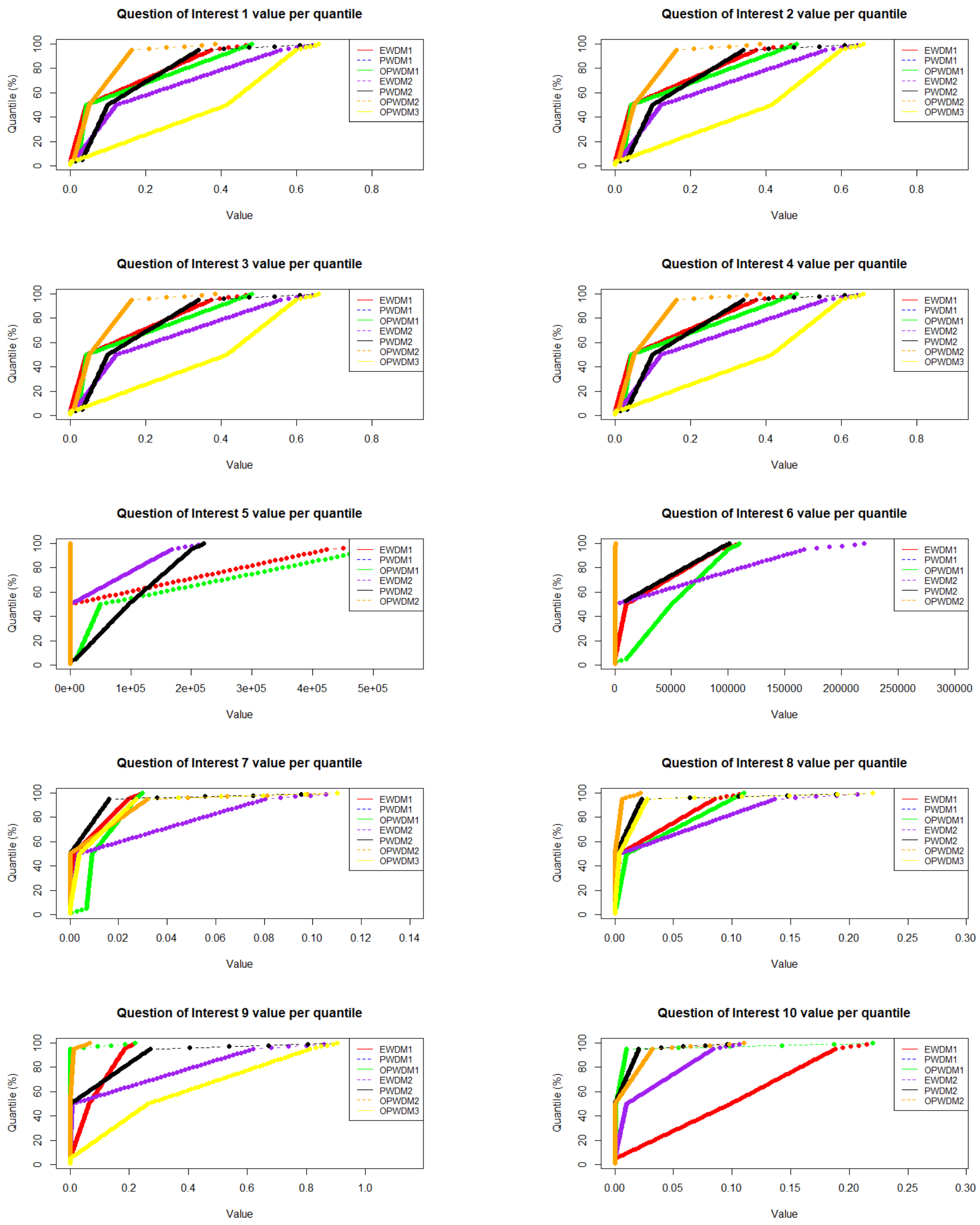

Figure G.1: Distributions of the decision makers for Question of Interest 1-10, with 11 calibration questions taken into account.

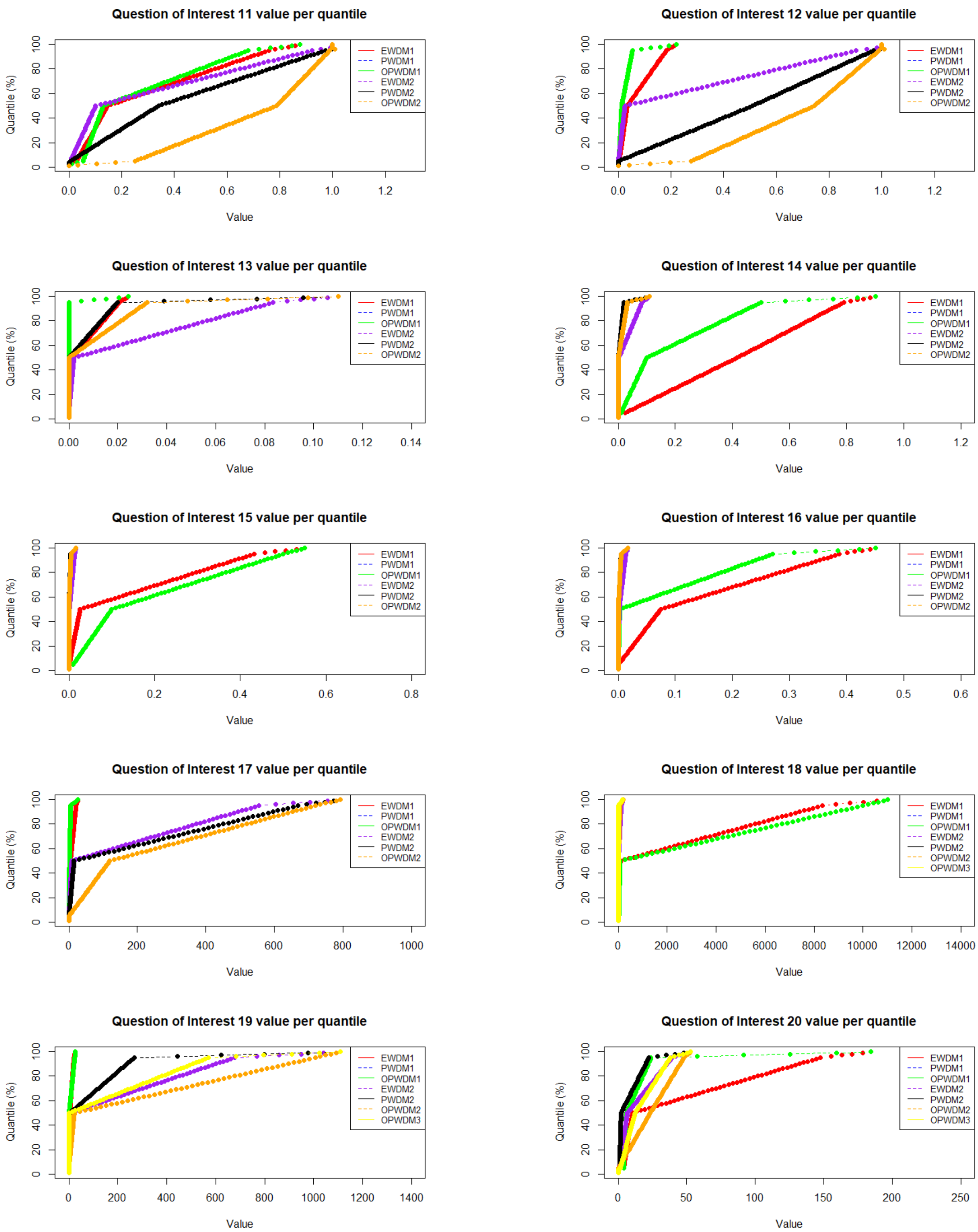

Figure G.2: Distributions of the decision makers for Question of Interest 11-20, with 11 calibration questions taken into account.

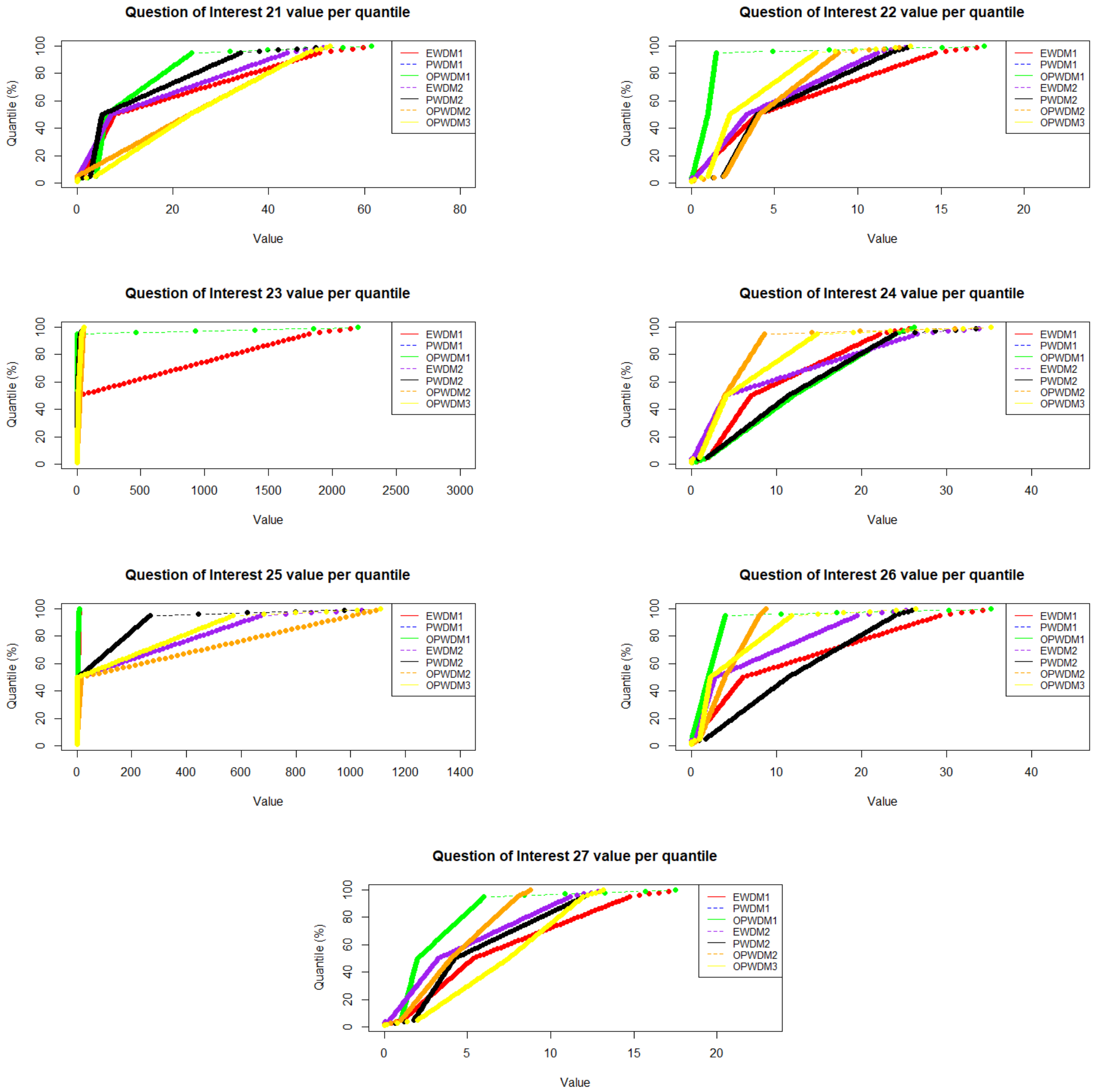

Figure G.3: Distributions of the decision makers for Question of Interest 21-27, with 11 calibration questions taken into account.

Desicion maker	**Description**
EWDM1	Equal-Weighted Decision Maker with 9 experts but without the questions of interest that have not been answered by an expert.
EWDM2	Equal-Weighted Decision Maker with all the questions of interest taken into account but without the experts that did not answer some of the question of interest.
PWDM1	Performance Weighted Decision Maker with 9 experts but without the questions of interest that have not been answered by an expert.
PWDM2	Performance Weighted Decision Maker with all the questions of interest taken into account but without the experts that did not answer some of the question of interest.

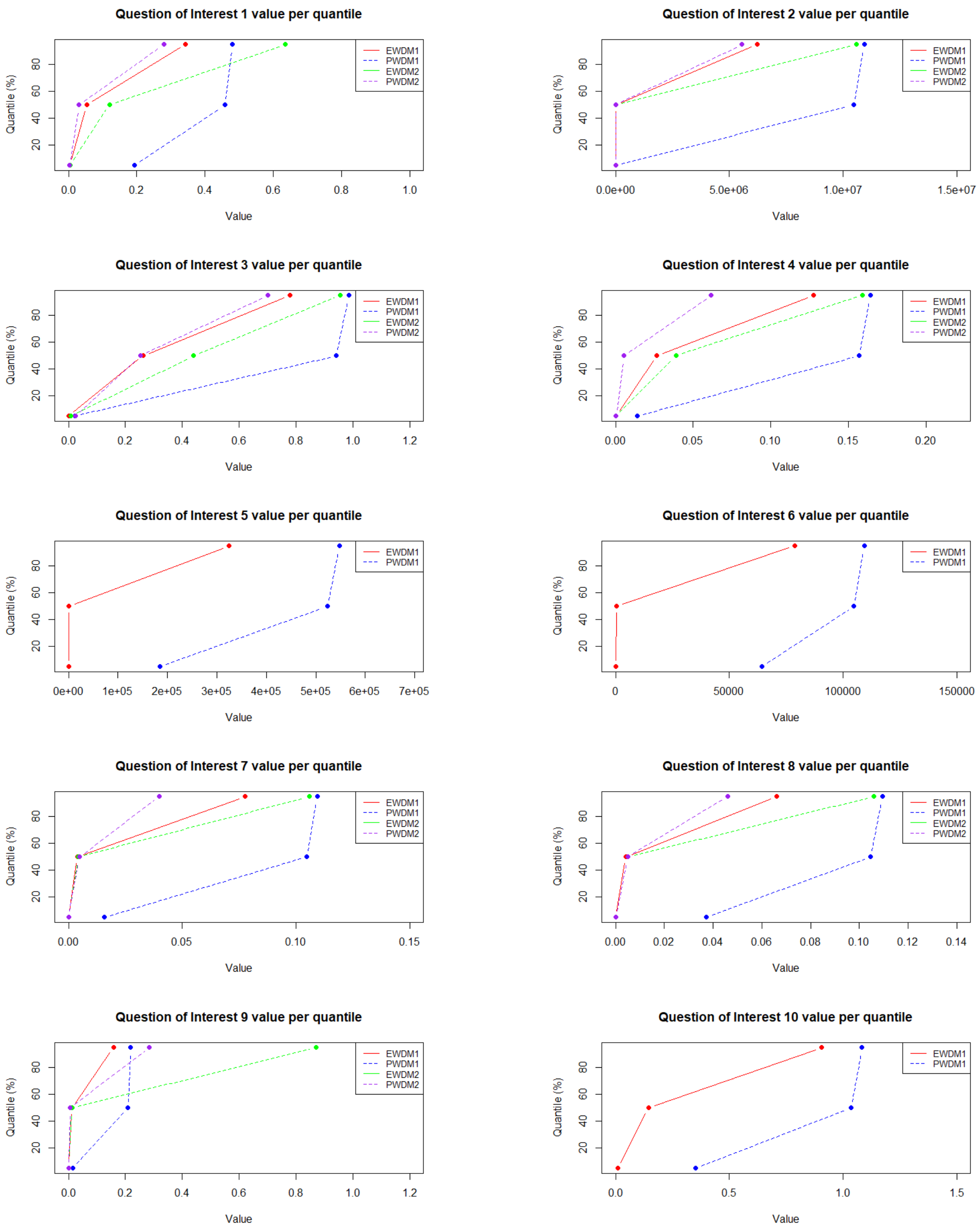

Figure G.4: Distributions of the decision makers for Question of Interest 1-12, with 7 calibration questions taken into account.

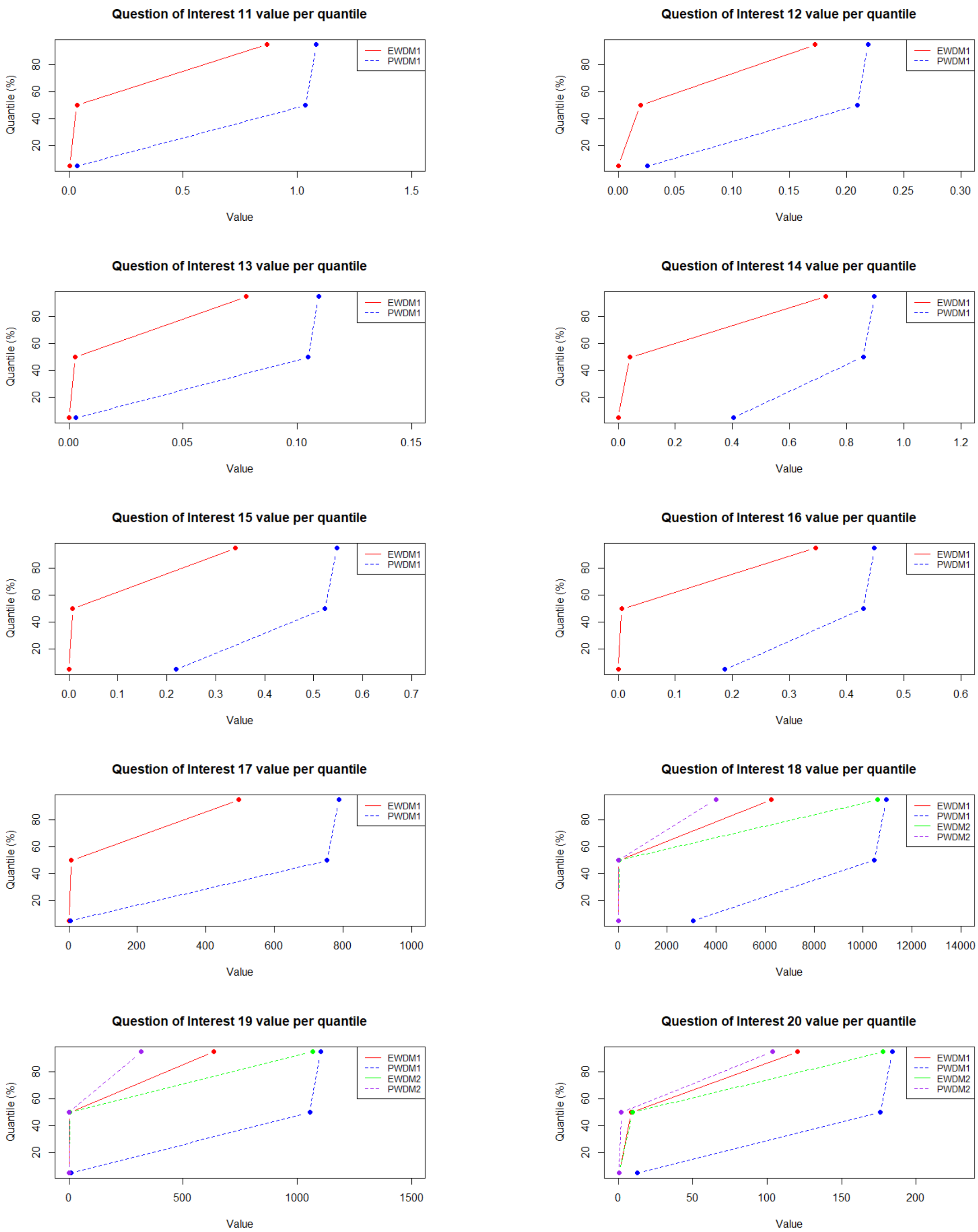

Figure G.5: Distributions of the decision makers for Question of Interest 13-24, with 7 calibration questions taken into account.

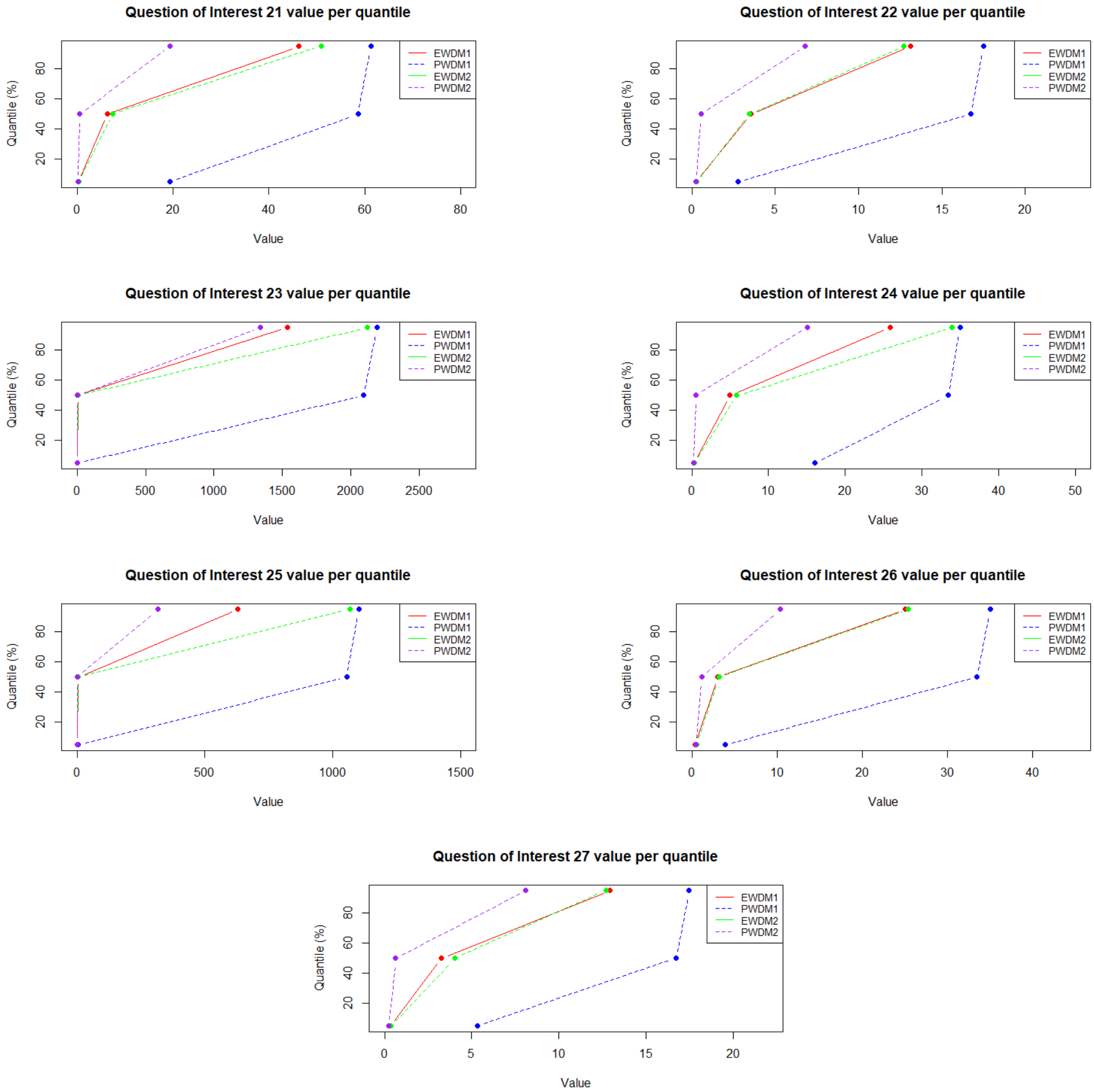

Figure G.6: Distributions of the decision makers for Question of Interest 25-27, with 7 calibration questions taken into account.

Appendix H

Scores of the decision makers

Below 5 tables are given, which give insight in the scores of the decision makers. Table H.1 shows the scores of case 1 with decision makers EWDM, PWDM, and OPWDM. The assessment of expert E3 is below the 5%- quantile. Table H.2 displays the scores of case 2 with decision makers EWDM, PWDM, and OPWDM. The assessment of E3 lays between the 5%- and 50%- quantile interval. Next, Table H.3 is about case 3 with decision makers EWDM, PWDM, and OPWDM. The assessment of expert E3 is considered to be between the 50%- and 95%- quantile interval. Then Table H.4 is given which is about case 4 with decision makers EWDM, PWDM, and OPWDM. Expert E3 has an overestimated assessment, i.e. it lays in the $>$ 95%- quantile. At last, Table H.5 shows the scores of case 5 with decision makers EWDM, PWDM, and OPWDM. The assessment of the calibration question that expert E3 did not answer is deleted for every expert.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.09406	0.6432	0.2767	0.02603
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.01088	1.833	0.6298	0.00685
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.01088	1.601	0.6258	0.006807
OPWDM2	4.845E-005	1.606	1.194	5.783E-005
OPWDM3	0.01088	1.009	0.9613	0.01046

Table H.1: Case 1 with decision makers EWDM, PWDM, and OPWDM. The realization is assumed to be below Expert's E3's 5%- quantile. The highest scores are indicated in green.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.09406	0.6432	0.2774	0.02609
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.01088	1.425	0.6008	0.006535
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.01088	1.833	0.6298	0.00685
OPWDM2	4.845E-005	1.606	1.194	5.783E-005
OPWDM3	0.01088	1.009	0.9613	0.01046

Table H.2: Case 2 with decision makers EWDM, PWDM, and OPWDM. The realization is assumed to be between Expert's E3's 5%- and 50%- quantile. The highest scores are indicated in green.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.09406	0.6435	0.278	0.02615
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.06362	1.144	0.466	0.03032
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.06362	1.145	0.477	0.03034
OPWDM2	4.845E-005	1.606	1.194	5.783E-005
OPWDM3	0.01088	1.009	0.9613	0.01046

Table H.3: Case 3 with decision makers EWDM, PWDM, and OPWDM. The realization is assumed to be between Expert's E3's 50%- and 95%- quantile. The highest scores are indicated in green.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.09406	0.6437	0.2786	0.02621
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.01088	1.564	0.62328	0.006779
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.01088	1.564	0.6232	0.006779
OPWDM2	4.845E-005	1.606	1.194	5.783E-005
OPWDM3	0.01088	1.009	0.9613	0.01046

Table H.4: Case 4 with decision makers EWDM, PWDM, and OPWDM. The realization is assumed to be above Expert's E3's 95%- quantile. The highest scores are indicated in green.

Expert ID	Calibration score	Information scores total	Information score calibration questions	Combined score
EWDM1a	0.0322	0.6556	0.2882	0.00951
EWDM1b	0.06362	0.7725	0.6226	0.03961
PWDM1a	0.00599	1.868	0.6411	0.003841
PWDM1b	0.01088	1.214	1.006	0.01094
OPWDM1	0.00599	1.401	0.5957	0.003568
OPWDM2	1.579E-005	1.293	1.18	1.863E-005
OPWDM3	0.008214	1.013	0.9452	0.007764

Table H.5: Case 5 with decision makers EWDM, PWDM, and OPWDM. The assessment of the calibration question that expert E3 did not answer is deleted for every expert. The highest scores are indicated in green.

Appendix I

Files used in UNINET

The random variables which are assigned a distribution through files in UNINET and the corresponding distribution are shown below.

Quantile	D2	D3	E2	F1	G1	G2	NC1	ND2	ND3
00.25	9,56E-09	1,89E-09	5,90E-06	0,000000658	0,000000983	1,59E-09	0,1248	0,205	0,015
01.00	1,123E-08	3,58E-09	7,20E-06	0,000007853	0,000001586	3,45E-09	0,153	0,2113	0,0221
02.00	1,57E-08	5,12E-09	8,20E-06	0,0000135	0,000004321	5,87E-09	0,1758	0,2176	0,0275
03.00	2,85E-08	7,58E-09	8,70E-06	0,0000735	0,000005624	7,34E-09	0,1986	0,2205	0,0308
04.00	1,50E-07	8,02E-09	1,08E-05	0,00032	0,000008595	8,58E-09	0,2514	0,2314	0,043
05.00	1,578E-07	9,87E-09	1,27E-05	0,0004197	0,00001235	9,88E-09	0,2913	0,2548	0,0466
06.00	7,295E-05	8,12E-07	0,000101	0,001004	0,0002635	5,98E-06	0,4199	0,4691	0,1161
07.00	0,0001457	1,62E-06	0,000189	0,001589	0,0005147	1,2E-05	0,5484	0,6834	0,1856
08.00	0,0002185	2,42E-06	0,000277	0,002173	0,0007659	1,79E-05	0,677	0,8977	0,2551
09.00	0,0002913	3,22E-06	0,000365	0,002758	0,001017	2,39E-05	0,8056	1,112	0,3246
10.00	0,0003641	4,02E-06	0,000453	0,003342	0,001268	2,99E-05	0,9341	1,326	0,3942
11.00	0,0004369	4,83E-06	0,00054	0,003927	0,001519	3,59E-05	1,063	1,541	0,4637
12.00	0,0005097	5,63E-06	0,000628	0,004512	0,001771	4,18E-05	1,191	1,755	0,5332
13.00	0,0005825	6,43E-06	0,000716	0,005096	0,002022	4,78E-05	1,32	1,969	0,6027
14.00	0,0006553	7,23E-06	0,000804	0,005681	0,002273	5,38E-05	1,448	2,184	0,6722
15.00	0,0007281	8,04E-06	0,000892	0,006265	0,002524	5,98E-05	1,577	2,398	0,7417
16.00	0,0008009	8,84E-06	0,00098	0,00685	0,002775	6,57E-05	1,705	2,612	0,8112
17.00	0,0008737	9,64E-06	0,001068	0,007434	0,003027	7,17E-05	1,834	2,826	0,8808
18.00	0,0009465	1,04E-05	0,001156	0,008019	0,003278	7,77E-05	1,963	3,041	0,9503
19.00	0,001019	1,13E-05	0,001244	0,008603	0,003529	8,37E-05	2,091	3,255	1,02
20.00	0,001092	1,21E-05	0,001332	0,009188	0,00378	8,96E-05	2,22	3,469	1,089
21.00	0,001165	1,29E-05	0,00142	0,009772	0,004031	9,56E-05	2,348	3,684	1,159

Quantile	NE1	NE2	NF1	NF2	NG1	NG2	NG3	NH1	NH3	LE1	HE1	LF2	HF2	LG3	HG3
00.25	0,1256	0,1123	0,1354	0,05025	0,2035	0,0132	0,2831	0,1832	0,00956	2E-11	0,001035	1E-14	0,0002035	5E-11	0,00002056
01.00	0,2198	0,1624	0,1761	0,08064	0,2365	0,01524	0,3204	0,2235	0,0235	1,684E-10	0,001862	8,421E-14	0,0002351	4,21E-10	0,0000456
02.00	0,3218	0,2049	0,1953	0,125	0,2761	0,01984	0,3851	0,2765	0,0456	1,263E-09	0,002149	6,316E-13	0,0002589	3,158E-09	0,0000852
03.00	0,4358	0,2534	0,2135	0,1305	0,2865	0,02067	0,40235	0,30589	0,0956	8,414E-08	0,003256	4,211E-12	0,0003018	2,105E-08	0,000096
04.00	0,5864	0,3008	0,2564	0,1461	0,3086	0,02203	0,4682	0,3559	0,1076	4,201E-07	0,005756	2,105E-11	0,0003258	1,052E-07	0,000112
05.00	0,6266	0,3241	0,2824	0,1602	0,3343	0,02458	0,5033	0,356	0,1189	0,000001223	0,006145	4,78E-11	0,0003366	7,0856E-07	0,0001789
06.00	0,7896	0,4803	0,3522	0,3092	0,4469	0,1007	0,564	0,4366	2,65	0,0001417	0,008517	1,405E-08	0,0003477	0,0009229	0,0004922
07.00	0,9527	0,6364	0,4219	0,4583	0,5595	0,1769	0,6247	0,5172	5,181	0,0002712	0,01089	2,805E-08	0,0006697	0,001839	0,0008055
08.00	1,116	0,7926	0,4916	0,6073	0,672	0,2531	0,6854	0,5979	7,713	0,0004007	0,01326	4,205E-08	0,001003	0,002754	0,001119
09.00	1,279	0,9487	0,5614	0,7564	0,7846	0,3292	0,7461	0,6786	10,24	0,0005301	0,01563	5,605E-08	0,001336	0,00367	0,001432
10.00	1,442	1,105	0,6311	0,9054	0,8972	0,4054	0,8067	0,7593	12,78	0,0006596	0,01801	7,005E-08	0,001669	0,004586	0,001746
11.00	1,605	1,261	0,7009	1,055	1,01	0,4815	0,8674	0,84	15,31	0,0007891	0,02038	8,405E-08	0,002002	0,005502	0,002059
12.00	1,768	1,417	0,7706	1,204	1,122	0,5577	0,9281	0,9207	17,84	0,0009186	0,02275	9,806E-08	0,002335	0,006418	0,002372
13.00	1,931	1,573	0,8403	1,353	1,235	0,6339	0,9888	1,001	20,37	0,001048	0,02512	1,121E-07	0,002668	0,007333	0,002686
14.00	2,094	1,73	0,9101	1,502	1,348	0,71	1,049	1,082	22,9	0,001178	0,02749	1,261E-07	0,003001	0,008249	0,002999
15.00	2,257	1,886	0,9798	1,651	1,46	0,7862	1,11	1,163	25,43	0,001307	0,02987	1,401E-07	0,003335	0,009165	0,003312
16.00	2,42	2,042	1,05	1,8	1,573	0,8623	1,171	1,243	27,96	0,001436	0,03224	1,541E-07	0,003668	0,01008	0,003626
17.00	2,583	2,198	1,119	1,949	1,685	0,9385	1,231	1,324	30,49	0,001566	0,03461	1,681E-07	0,004001	0,011	0,003939
18.00	2,746	2,354	1,189	2,098	1,798	1,015	1,292	1,405	33,03	0,001695	0,03698	1,821E-07	0,004334	0,01191	0,004252
19.00	2,909	2,51	1,259	2,247	1,91	1,091	1,353	1,485	35,56	0,001825	0,03935	1,961E-07	0,004667	0,01283	0,004566
20.00	3,072	2,666	1,329	2,396	2,023	1,167	1,414	1,566	38,09	0,001954	0,04173	2,101E-07	0,005	0,01374	0,004879
21.00	3,235	2,823	1,398	2,545	2,136	1,243	1,474	1,647	40,62	0,002084	0,0441	2,241E-07	0,005333	0,01466	0,005192

Quantile	D2	D3	E2	F1	G1	G2	NC1	ND2	ND3	NE1	NE2	NF1	NF2	NG1	NG2	NG3	NH1	NH3	LE1	HE1	LF2	HF2	LG3	HG3
22.00	0,001238	1,37E-05	0,001508	0,01036	0,004282	0,000102	2,477	3,898	1,228	3,398	2,979	1,468	2,694	2,248	1,319	1,535	1,727	43,15	0,002213	0,04647	2,381E-07	0,005666	0,01558	0,005506
23.00	0,00131	1,45E-05	0,001596	0,01094	0,004534	0,000108	2,605	4,112	1,298	3,561	3,135	1,538	2,843	2,361	1,395	1,596	1,808	45,68	0,002343	0,04884	2,521E-07	0,005999	0,01649	0,005819
24.00	0,001383	1,53E-05	0,001684	0,01153	0,004785	0,000114	2,734	4,327	1,367	3,724	3,291	1,607	2,992	2,473	1,472	1,656	1,889	48,21	0,002472	0,05122	2,661E-07	0,006333	0,01741	0,006132
25.00	0,001456	1,61E-05	0,001772	0,01211	0,005036	0,00012	2,863	4,541	1,437	3,887	3,447	1,677	3,141	2,586	1,548	1,717	1,97	50,74	0,002602	0,05359	2,801E-07	0,006666	0,01832	0,006446
26.00	0,001529	1,69E-05	0,00186	0,0127	0,005287	0,000126	2,991	4,755	1,506	4,05	3,603	1,747	3,29	2,699	1,624	1,778	2,05	53,28	0,002731	0,05596	2,941E-07	0,006999	0,01924	0,006759
27.00	0,001602	1,77E-05	0,001948	0,01328	0,005538	0,000131	3,12	4,969	1,576	4,213	3,76	1,817	3,439	2,811	1,7	1,838	2,131	55,81	0,002861	0,05833	3,081E-07	0,007332	0,02015	0,007072
28.00	0,001674	1,85E-05	0,002036	0,01386	0,00579	0,000137	3,248	5,184	1,645	4,376	3,916	1,886	3,588	2,924	1,776	1,899	2,212	58,34	0,00299	0,0607	3,221E-07	0,007665	0,02107	0,007386
29.00	0,001747	1,93E-05	0,002124	0,01445	0,006041	0,000143	3,377	5,398	1,715	4,539	4,072	1,956	3,738	3,036	1,852	1,96	2,292	60,87	0,00312	0,06308	3,361E-07	0,007998	0,02199	0,007699
30.00	0,00182	2,01E-05	0,002212	0,01503	0,006292	0,000149	3,505	5,612	1,784	4,702	4,228	2,026	3,887	3,149	1,929	2,02	2,373	63,4	0,003249	0,06545	3,501E-07	0,008331	0,0229	0,008012
31.00	0,001893	2,09E-05	0,0023	0,01562	0,006543	0,000155	3,634	5,827	1,854	4,865	4,384	2,096	4,036	3,261	2,005	2,081	2,454	65,93	0,003379	0,06782	3,641E-07	0,008664	0,02382	0,008326
32.00	0,001966	2,17E-05	0,002388	0,0162	0,006794	0,000161	3,762	6,041	1,923	5,028	4,54	2,165	4,185	3,374	2,081	2,142	2,534	68,46	0,003508	0,07019	3,781E-07	0,008997	0,02473	0,008639
33.00	0,002038	2,25E-05	0,002476	0,01679	0,007045	0,000167	3,891	6,255	1,993	5,191	4,697	2,235	4,334	3,487	2,157	2,202	2,615	70,99	0,003638	0,07256	3,921E-07	0,009331	0,02565	0,008953
34.00	0,002111	2,33E-05	0,002564	0,01737	0,007297	0,000173	4,02	6,47	2,062	5,354	4,853	2,305	4,483	3,599	2,233	2,263	2,696	73,53	0,003767	0,07494	4,061E-07	0,009664	0,02657	0,009266
35.00	0,002184	2,41E-05	0,002652	0,01796	0,007548	0,000179	4,148	6,684	2,132	5,517	5,009	2,375	4,632	3,712	2,309	2,324	2,776	76,06	0,003896	0,07731	4,201E-07	0,009997	0,02748	0,009579
36.00	0,002257	2,49E-05	0,00274	0,01854	0,007799	0,000185	4,277	6,898	2,201	5,68	5,165	2,444	4,781	3,824	2,386	2,384	2,857	78,59	0,004026	0,07968	4,341E-07	0,01033	0,0284	0,009893
37.00	0,00233	2,57E-05	0,002827	0,01913	0,00805	0,000191	4,405	7,112	2,271	5,843	5,321	2,514	4,93	3,937	2,462	2,445	2,938	81,12	0,004155	0,08205	4,481E-07	0,01066	0,02931	0,01021
38.00	0,002402	2,65E-05	0,002915	0,01971	0,008301	0,000197	4,534	7,327	2,341	6,006	5,477	2,584	5,079	4,049	2,538	2,506	3,018	83,65	0,004285	0,08443	4,621E-07	0,011	0,03023	0,01052
39.00	0,002475	2,73E-05	0,003003	0,02029	0,008553	0,000203	4,662	7,541	2,41	6,169	5,633	2,654	5,228	4,162	2,614	2,566	3,099	86,18	0,004414	0,0868	4,761E-07	0,01133	0,03114	0,01083
40.00	0,002548	2,81E-05	0,003091	0,02088	0,008804	0,000209	4,791	7,755	2,48	6,332	5,79	2,723	5,377	4,275	2,69	2,627	3,18	88,71	0,004544	0,08917	4,901E-07	0,01166	0,03206	0,01115
41.00	0,002621	2,89E-05	0,003179	0,02146	0,009055	0,000215	4,92	7,97	2,549	6,495	5,946	2,793	5,526	4,387	2,766	2,688	3,26	91,24	0,004673	0,09154	5,041E-07	0,012	0,03298	0,01146
42.00	0,002694	2,97E-05	0,003267	0,02205	0,009306	0,000221	5,048	8,184	2,619	6,658	6,102	2,863	5,675	4,5	2,842	2,748	3,341	93,78	0,004803	0,09391	5,181E-07	0,01233	0,03389	0,01177
43.00	0,002766	3,05E-05	0,003355	0,02263	0,009557	0,000227	5,177	8,398	2,688	6,821	6,258	2,932	5,824	4,612	2,919	2,809	3,422	96,31	0,004932	0,09629	5,321E-07	0,01266	0,03481	0,01209
44.00	0,002839	3,13E-05	0,003443	0,02322	0,009808	0,000233	5,305	8,613	2,758	6,984	6,414	3,002	5,973	4,725	2,995	2,87	3,503	98,84	0,005062	0,09866	5,461E-07	0,01299	0,03572	0,0124

Quantile	D2	D3	E2	F1	G1	G2	NC1	ND2	ND3	NE1	NE2	NF1	NF2	NG1	NG2	NG3	NH1	NH3	LE1	HE1	LF2	HF2	LG3	HG3
44.00	0,002839	3,13E-05	0,003443	0,02322	0,009808	0,000233	5,305	8,613	2,758	6,984	6,414	3,002	5,973	4,725	2,995	2,87	3,503	98,84	0,005062	0,09866	5,461E-07	0,01299	0,03572	0,0124
45.00	0,002912	3,21E-05	0,003531	0,0238	0,01006	0,000239	5,434	8,827	2,827	7,147	6,57	3,072	6,122	4,838	3,071	2,931	3,583	101,4	0,005191	0,101	5,601E-07	0,01333	0,03664	0,01271
46.00	0,002985	3,29E-05	0,003619	0,02439	0,01031	0,000245	5,562	9,041	2,897	7,31	6,727	3,142	6,271	4,95	3,147	2,991	3,664	103,9	0,005321	0,1034	5,741E-07	0,01366	0,03755	0,01303
47.00	0,003057	3,37E-05	0,003707	0,02497	0,01056	0,000251	5,691	9,255	2,966	7,473	6,883	3,211	6,421	5,063	3,223	3,052	3,745	106,4	0,00545	0,1058	5,881E-07	0,01399	0,03847	0,01334
48.00	0,00313	3,45E-05	0,003795	0,02556	0,01081	0,000257	5,819	9,47	3,036	7,636	7,039	3,281	6,57	5,175	3,299	3,113	3,825	109	0,00558	0,1081	6,021E-07	0,01433	0,03939	0,01365
49.00	0,003203	3,53E-05	0,003883	0,02614	0,01106	0,000263	5,948	9,684	3,105	7,799	7,195	3,351	6,719	5,288	3,376	3,173	3,906	111,5	0,005709	0,1105	6,161E-07	0,01466	0,0403	0,01397
50.00	0,003276	3,61E-05	0,003971	0,02672	0,01132	0,000269	6,077	9,898	3,175	7,962	7,351	3,421	6,868	5,4	3,452	3,234	3,987	114	0,005839	0,1129	6,301E-07	0,01499	0,04122	0,01428
51.00	0,004813	0,003368	0,005228	0,02914	0,02314	0,003611	16,42	133,5	15,67	10,24	8,216	3,626	38,41	5,837	15,83	3,699	4,182	123000	0,00932	0,1302	0,0007545	0,01844	0,05084	0,0299
52.00	0,00635	0,006699	0,006485	0,03155	0,03495	0,006954	26,77	257	28,16	12,51	9,081	3,832	69,95	6,273	28,2	4,164	4,378	245900	0,0128	0,1475	0,001503	0,02189	0,06047	0,04552
53.00	0,007887	0,01003	0,007742	0,03397	0,04677	0,0103	37,12	380,6	40,65	14,78	9,946	4,038	101,5	6,71	40,58	4,63	4,573	368900	0,01628	0,1647	0,002251	0,02534	0,07009	0,06114
54.00	0,009424	0,01336	0,008999	0,03638	0,05859	0,01364	47,47	504,1	53,14	17,06	10,81	4,243	133	7,146	52,95	5,095	4,769	491800	0,01977	0,182	0,002999	0,02879	0,07972	0,07676
55.00	0,01096	0,01669	0,01026	0,0388	0,07041	0,01698	57,82	627,7	65,64	19,33	11,68	4,449	164,6	7,582	65,33	5,56	4,965	614700	0,02325	0,1993	0,003747	0,03225	0,08934	0,09238
56.00	0,0125	0,02002	0,01151	0,04121	0,08223	0,02032	68,17	751,2	78,13	21,6	12,54	4,655	196,1	8,019	77,71	6,025	5,16	737600	0,02673	0,2166	0,004495	0,0357	0,09897	0,108
57.00	0,01404	0,02336	0,01277	0,04363	0,09405	0,02367	78,51	874,8	90,62	23,88	13,41	4,86	227,6	8,455	90,08	6,491	5,356	860500	0,03021	0,2339	0,005243	0,03915	0,1086	0,1236
58.00	0,01557	0,02669	0,01403	0,04604	0,1059	0,02701	88,86	998,3	103,1	26,15	14,27	5,066	259,2	8,892	102,5	6,956	5,551	983400	0,03369	0,2511	0,005992	0,0426	0,1182	0,1392
59.00	0,01711	0,03002	0,01528	0,04846	0,1177	0,03035	99,21	1122	115,6	28,42	15,14	5,272	290,7	9,328	114,8	7,421	5,747	1106000	0,03717	0,2684	0,00674	0,04605	0,1278	0,1549
60.00	0,01865	0,03335	0,01654	0,05087	0,1295	0,0337	109,6	1245	128,1	30,7	16	5,477	322,3	9,764	127,2	7,886	5,943	1229000	0,04066	0,2857	0,007488	0,0495	0,1375	0,1705
61.00	0,02018	0,03668	0,0178	0,05329	0,1413	0,03704	119,9	1369	140,6	32,97	16,87	5,683	353,8	10,2	139,6	8,352	6,138	1352000	0,04414	0,303	0,008236	0,05295	0,1471	0,1861
62.00	0,02172	0,04001	0,01905	0,0557	0,1532	0,04038	130,3	1493	153,1	35,24	17,73	5,889	385,3	10,64	152	8,817	6,334	1475000	0,04762	0,3203	0,008984	0,0564	0,1567	0,2017
63.00	0,02326	0,04334	0,02031	0,05812	0,165	0,04372	140,6	1616	165,6	37,52	18,6	6,094	416,9	11,07	164,3	9,282	6,529	1598000	0,0511	0,3375	0,009732	0,05985	0,1663	0,2173
64.00	0,0248	0,04668	0,02157	0,06053	0,1768	0,04707	151	1740	178,1	39,79	19,46	6,3	448,4	11,51	176,7	9,747	6,725	1721000	0,05458	0,3548	0,01048	0,0633	0,176	0,233
65.00	0,02633	0,05001	0,02282	0,06295	0,1886	0,05041	161,3	1863	190,6	42,06	20,33	6,506	480	11,95	189,1	10,21	6,921	1844000	0,05806	0,3721	0,01123	0,06675	0,1856	0,2486
66.00	0,02787	0,05334	0,02408	0,06536	0,2004	0,05375	171,6	1987	203	44,34	21,19	6,711	511,5	12,38	201,5	10,68	7,116	1967000	0,06155	0,3894	0,01198	0,0702	0,1952	0,2642

Quantile	D2	D3	E2	F1	G1	G2	NC1	ND2	ND3	NE1	NE2	NF1	NF2	NG1	NG2	NG3	NH1	NH3	LE1	HE1	LF2	HF2	LG3	HG3
67.00	0,02941	0,05667	0,02534	0,06778	0,2123	0,05709	182	2110	215,5	46,61	22,06	6,917	543	12,82	213,8	11,14	7,312	2090000	0,06503	0,4067	0,01272	0,07365	0,2048	0,2798
68.00	0,03094	0,06	0,02659	0,07019	0,2241	0,06044	192,3	2234	228	48,88	22,92	7,123	574,6	13,26	226,2	11,61	7,507	2213000	0,06851	0,424	0,01347	0,0771	0,2145	0,2954
69.00	0,03248	0,06333	0,02785	0,0726	0,2359	0,06378	202,7	2357	240,5	51,16	23,79	7,328	606,1	13,69	238,6	12,07	7,703	2336000	0,07199	0,4412	0,01422	0,08055	0,2241	0,3111
70.00	0,03402	0,06666	0,02911	0,07502	0,2477	0,06712	213	2481	253	53,43	24,65	7,534	637,7	14,13	251	12,54	7,899	2458000	0,07547	0,4585	0,01497	0,084	0,2337	0,3267
71.00	0,03556	0,07	0,03037	0,07743	0,2595	0,07046	223,4	2605	265,5	55,7	25,52	7,74	669,2	14,56	263,3	13	8,094	2581000	0,07895	0,4758	0,01572	0,08745	0,2433	0,3423
72.00	0,03709	0,07333	0,03162	0,07985	0,2713	0,07381	233,7	2728	278	57,98	26,38	7,945	700,7	15	275,7	13,47	8,29	2704000	0,08244	0,4931	0,01647	0,0909	0,253	0,3579
73.00	0,03863	0,07666	0,03288	0,08226	0,2832	0,07715	244,1	2852	290,5	60,25	27,25	8,151	732,3	15,44	288,1	13,93	8,485	2827000	0,08592	0,5104	0,01721	0,09435	0,2626	0,3735
74.00	0,04017	0,07999	0,03414	0,08468	0,295	0,08049	254,4	2975	303	62,52	28,11	8,357	763,8	15,87	300,5	14,4	8,681	2950000	0,0894	0,5276	0,01796	0,0978	0,2722	0,3892
75.00	0,0417	0,08332	0,03539	0,08709	0,3068	0,08383	264,8	3099	315,5	64,8	28,98	8,562	795,4	16,31	312,8	14,86	8,877	3073000	0,09288	0,5449	0,01871	0,1013	0,2819	0,4048
76.00	0,04324	0,08665	0,03665	0,08951	0,3186	0,08718	275,1	3222	328	67,07	29,84	8,768	826,9	16,75	325,2	15,33	9,072	3196000	0,09636	0,5622	0,01946	0,1047	0,2915	0,4204
77.00	0,04478	0,08999	0,03791	0,09192	0,3304	0,09052	285,5	3346	340,5	69,34	30,71	8,974	858,4	17,18	337,6	15,8	9,268	3319000	0,09984	0,5795	0,02021	0,1082	0,3011	0,436
78.00	0,04631	0,09332	0,03916	0,09434	0,3423	0,09386	295,8	3469	353	71,62	31,57	9,179	890	17,62	350	16,26	9,463	3442000	0,1033	0,5968	0,02095	0,1116	0,3107	0,4516
79.00	0,04785	0,09665	0,04042	0,09675	0,3541	0,09721	306,2	3593	365,4	73,89	32,44	9,385	921,5	18,06	362,3	16,73	9,659	3565000	0,1068	0,6141	0,0217	0,1151	0,3204	0,4673
80.00	0,04939	0,09998	0,04168	0,09917	0,3659	0,1005	316,5	3716	377,9	76,16	33,3	9,591	953,1	18,49	374,7	17,19	9,855	3688000	0,1103	0,6313	0,02245	0,1185	0,33	0,4829
81.00	0,05093	0,1033	0,04293	0,1016	0,3777	0,1039	326,9	3840	390,4	78,44	34,17	9,796	984,6	18,93	387,1	17,66	10,05	3811000	0,1138	0,6486	0,0232	0,122	0,3396	0,4985
82.00	0,05246	0,1066	0,04419	0,104	0,3895	0,1072	337,2	3964	402,9	80,71	35,03	10	1016	19,37	399,5	18,12	10,25	3933000	0,1173	0,6659	0,02395	0,1254	0,3492	0,5141
83.00	0,054	0,11	0,04545	0,1064	0,4014	0,1106	347,6	4087	415,4	82,98	35,9	10,21	1048	19,8	411,8	18,59	10,44	4056000	0,1207	0,6832	0,0247	0,1289	0,3589	0,5297
84.00	0,05554	0,1133	0,04671	0,1088	0,4132	0,1139	357,9	4211	427,9	85,26	36,76	10,41	1079	20,24	424,2	19,05	10,64	4179000	0,1242	0,7005	0,02544	0,1323	0,3685	0,5454
85.00	0,05707	0,1166	0,04796	0,1112	0,425	0,1173	368,3	4334	440,4	87,53	37,63	10,62	1111	20,67	436,6	19,52	10,83	4302000	0,1277	0,7177	0,02619	0,1358	0,3781	0,561
86.00	0,05861	0,12	0,04922	0,1137	0,4368	0,1206	378,6	4458	452,9	89,8	38,49	10,82	1142	21,11	449	19,98	11,03	4425000	0,1312	0,735	0,02694	0,1392	0,3877	0,5766
87.00	0,06015	0,1233	0,05048	0,1161	0,4486	0,1239	389	4581	465,4	92,08	39,36	11,03	1174	21,55	461,4	20,45	11,22	4548000	0,1347	0,7523	0,02769	0,1427	0,3974	0,5922
88.00	0,06169	0,1266	0,05173	0,1185	0,4605	0,1273	399,3	4705	477,9	94,35	40,22	11,24	1205	21,98	473,7	20,91	11,42	4671000	0,1381	0,7696	0,02844	0,1461	0,407	0,6078

Quantile	D2	D3	E2	F1	G1	G2	NC1	ND2	ND3	NE1	NE2	NF1	NF2	NG1	NG2	NG3	NH1	NH3	LE1	HE1	LF2	HF2	LG3	HG3
89.00	0,06322	0,13	0,05299	0,1209	0,4723	0,1306	409,7	4828	490,4	96,62	41,09	11,44	1237	22,42	486,1	21,38	11,62	4794000	0,1416	0,7869	0,02918	0,1496	0,4166	0,6235
90.00	0,06476	0,1333	0,05425	0,1233	0,4841	0,134	420	4952	502,9	98,9	41,95	11,65	1268	22,86	498,5	21,84	11,81	4917000	0,1451	0,8041	0,02993	0,153	0,4262	0,6391
91.00	0,0663	0,1366	0,0555	0,1257	0,4959	0,1373	430,4	5076	515,4	101,2	42,82	11,85	1300	23,29	510,9	22,31	12,01	5040000	0,1486	0,8214	0,03068	0,1565	0,4359	0,6547
92.00	0,06783	0,14	0,05676	0,1281	0,5077	0,1407	440,7	5199	527,8	103,4	43,68	12,06	1332	23,73	523,2	22,77	12,2	5163000	0,1521	0,8387	0,03143	0,1599	0,4455	0,6703
93.00	0,06937	0,1433	0,05802	0,1306	0,5196	0,144	451	5323	540,3	105,7	44,55	12,26	1363	24,17	535,6	23,24	12,4	5286000	0,1556	0,856	0,03218	0,1634	0,4551	0,6859
94.00	0,07091	0,1466	0,05927	0,133	0,5314	0,1473	461,4	5446	552,8	108	45,41	12,47	1395	24,6	548	23,7	12,59	5408000	0,159	0,8733	0,03292	0,1668	0,4647	0,7016
95.00	0,07245	0,15	0,06053	0,1354	0,5432	0,1507	471,7	5570	565,3	110,3	46,28	12,68	1426	25,04	560,4	24,17	12,79	5531000	0,1625	0,8906	0,03367	0,1703	0,4744	0,7172
96.00	0,08035	0,1647	0,07095	0,1416	0,6192	0,1653	539,2	6713	679,7	126	49,51	13,71	1589	27,17	675,8	26,49	13,8	6683000	0,1746	0,9322	0,04974	0,1807	0,4903	0,7561
97.00	0,08826	0,1794	0,08136	0,1479	0,6952	0,1799	606,6	7856	794,2	141,6	52,73	14,75	1752	29,31	791,3	28,81	14,8	7834000	0,1867	0,9739	0,06581	0,1912	0,5062	0,795
98.00	0,09616	0,1942	0,09177	0,1541	0,7712	0,1945	674	8999	908,6	157,3	55,96	15,78	1915	31,44	906,7	31,13	15,81	8985000	0,1988	0,9780	0,08188	0,2017	0,5221	0,8339
99.00	0,1041	0,2089	0,1022	0,1603	0,8472	0,2091	741,4	10140	1023	173	59,18	16,82	2078	33,57	1022	33,45	16,82	10140000	0,2109	0,9827	0,09795	0,2121	0,5381	0,8728
99.75	0,11	0,22	0,11	0,165	0,9042	0,22	792	11000	1109	184,8	61,6	17,59	2200	35,18	1109	35,19	17,58	11000000	0,22	0,9950	0,11	0,22	0,55	0,902

Appendix J

Formulas for functional nodes from UNINET

In this Appendix three tables are give. Table J.1 shows how the functional nodes from UNINET regarding to probability values are derivated in the BN. The second table, Table J.2, shows how the functional nodes from UNINET regarding time values are derivated in the BN. The last table shows how the probabilities for the nodes E1, F2, and G3 are derivated in the EBN. This is Table J.3.

$D1\_FUNCTIONAL ==$	$1-(1-B1)*(1-C1)*(1-D2)$
$D4\_FUNCTIONAL ==$	$1-D1\_FUNCTIONAL$
$E1\_FUNCTIONAL ==$	$1-(1-C1)*(1-D1\_FUNCTIONAL)*(1-E2)*D4\_FUNCTIONAL-(1-C1)*D1\_FUNCTIONAL*(1-D4\_FUNCTIONAL)*(1-E2)$
$F2\_FUNCTIONAL ==$	$E1\_FUNCTIONAL*E2$
$G3\_FUNCTIONAL ==$	$G1*F2\_FUNCTIONAL$
$H1\_FUNCTIONAL ==$	$G3\_FUNCTIONAL$
$H2\_FUNCTIONAL ==$	$1-(1-E1\_FUNCTIONAL)*(1-F1)*(1-E2)*(1-F2\_FUNCTIONAL)*(1-G1)*(1-G2)*(1-G3\_FUNCTIONAL)*(1-H1\_FUNCTIONAL)$

Table J.1: Derivation of the functional nodes regarding probability values in the BN.

$C1NC1 ==$	$C1 * NC1$
$D2ND2 ==$	$D2 * ND2 + D2 * D3 * D3ND3$
$D3ND3 ==$	$ND3 * D3$
$E1NE1 ==$	$NE1 * E1\_FUNCTIONAL$
$E2NE2 ==$	$E2 * NE2$
$F1NF1 ==$	$F1 * NF1$
$F2NF2 ==$	$NF2 * F2\_FUNCTIONAL$
$G1NG1 ==$	$NG1 * G1 + G1 * G2 * G2NG2$
$G2NG2 ==$	$G2 * NG2$
$G3NG3 ==$	$NG3 * G3\_FUNCTIONAL$
$H1NH1 ==$	$H1\_FUNCTIONAL * NH1$
$H3\_FUNCTIONAL ==$	$(E1\_FUNCTIONAL * E1NE1 + F1 * F1NF1 + E2 * E2NE2 + F2\_FUNCTIONAL * F2NF2 + G1 * G1NG1 + G2 * G2NG2 + G3\_FUNCTIONAL * G3NG3 + H1\_FUNCTIONAL * H1NH1) * H2\_FUNCTIONAL$

Table J.2: Derivation of the functional nodes regarding time values in the BN.

$E1\_FUNCTIONAL ==$	$if(I == 0, LE1 * (1 - (1 - C1) * (1 - D1_FUNCTIONAL) * (1 - E2) * D4\_FUNCTIONAL - (1 - C1) * D1\_FUNCTIONAL * (1 - D4\_FUNCTIONAL) * (1 - E2)), HE1 * (1 - (1 - C1) * (1 - D1\_FUNCTIONAL) * (1 - E2) * D4\_FUNCTIONAL - (1 - C1) * D1\_FUNCTIONAL * (1 - D4\_FUNCTIONAL) * (1 - E2)))$
$F2\_FUNCTIONAL ==$	$if(I == 0, LF2 * E1\_FUNCTIONAL * E2, HF2 * E1\_FUNCTIONAL * E2)$
$G3\_FUNCTIONAL ==$	$if(I == 0, LG3 * G1 * F2\_FUNCTIONAL, HG3 * G1 * F2\_FUNCTIONAL)$

Table J.3: Derivation of the functional nodes E1, F2, and G3 regarding probability values in the EBN.

Appendix **K**

Defining probabilities of the functional nodes in UNINET

In this Appendix three tables are given. Table K.1 shows how the probabilities for each yellow functional node in UNINET is defined. Next, Table K.2 shows how the probabilities for each white functional node corresponding to the time, t, is defined. The last table shows how the probabilities for the additional nodes in the EBN are defined, see Table K.3.

P(D1=0) =	P(B1=0)P(C1=0)P(D2=0)
P(D1=1)=	1-P(D1=0)
P(D4=x) =	1-P(D1=x), x=0,1
P(E1=0) =	P(C1=0)P(E2=0)(P(D1=0)P(D4=0)+P(D1=1)P(D4=0)+P(D1=0)P(D4=1))
P(E1=1) =	1-P(E1=0)
P(F2=0) =	P(E1=0)P(E2=0)
P(F2=1) =	1-P(F2=0)
P(G3=0) =	P(G1=0)P(F2=0)
P(G3=1) =	1-P(G3=0)
P(H1=x) =	P(G3=x), x=0,1
P(H2=1) =	P(E1=0)($\sum_{a,...,g=0,1}$P(E2=a)P(F1=b)P(F2=c)P(G1=d)P(G2=e)P(G3=f)P(H1=g))
	+P(E2=1)P(E1=1)($\sum_{a,...,f=0,1}$P(F1=a)P(F2=b)P(G1=c)P(G2=d)P(G3=e)P(H1=f))
	+P(F2=0)P(E2=0)P(E1=1)($\sum_{a,...,e=0,1}$P(F1=a)P(G1=b)P(G2=c)P(G3=d)P(H1=e))
	+P(G1=1)P(F2=1)P(E2=0)P(E1=1)($\sum_{a,...,d=0,1}$P(F1=a)P(G2=b)P(G3=c)P(H1=d))
	+P(G3=0)P(G1=0)P(F2=1)P(E2=0)P(E1=1)($\sum_{a,b,c=0,1}$P(F1=a)P(G2=b)P(H1=c))
	+P(H1=0)P(G3=1)P(G1=0)P(F2=1)P(E2=0)P(E1=1)($\sum_{a,b=0,1}$P(F1=a)P(G2=b))
P(H2=0) =	1-P(H2=1)

Table K.1: Probabilities of the yellow functional nodes.

P(C1NC1=t) =	P(NC1=t)(P(C1=0)+P(C1=1))
P(D2ND2=t) =	P(ND2=t)(P(D2=0)+P(D2=1))+P(ND3=t)P(D3=1)P(D2=1)
P(D3ND3=t) =	P(ND3=t)(P(D3=0)+P(D3=1))
P(E1NE1=t) =	P(NE1=t)(P(E1=0)+P(E1=1))
P(E2NE2=t) =	P(NE2=t)(P(E2=0)+P(E2=1))
P(F1NF1=t) =	P(NF1=t)(P(F1=0)+P(F1=1))
P(F2NF2=t) =	P(NF2=t)(P(F2=0)+P(F2=1))
P(G1NG1=t) =	P(NG1=t)(P(G1=0)+P(G1=1))+P(NG2=t)P(G2=1)P(G1=1)
P(G2NG2=t) =	P(NG2=t)(P(G2=0)+P(G2=1))
P(G3NG3=t) =	P(NG3=t)(P(G3=0)+P(G3=1))
P(H1NH1=t) =	P(NH1=t)(P(H1=0)+P(H1=1))
P(H3=t) =	P(H2=1)(P(E1NE1=t)P(E1=0)+P(E2NE2=t)P(E2=1)+ P(F1NF1=t)P(F1=1)P(F2=0)+P(F2NF2=t)P(F2=0)+ P(NGNG1=t)P(G1=1)+P(G2NG2=t)P(G2=1)P(G1=1)+ P(G3NG3=t)P(G3=0)+P(H1NH1=t)P(H1=0))

Table K.2: Probabilities of the white functional nodes.

P(E1=0) =	P(I=1)P(HE1=0)P(C1=0)P(E2=0)(P(D1=0)P(D4=0)+P(D1=1)P(D4=0) +P(D1=0)P(D4=1))+P(I=1)(LE1=0)P(C1=0)P(E2=0)(P(D1=0)P(D4=0) +P(D1=1)P(D4=0)+P(D1=0)P(D4=1))
P(E1=1) =	1-P(E1=0)
P(F2=0) =	(P(I=1)P(HF2=0)+P(I=0)P(LF2=0))P(E1=0)P(E2=0)
P(F2=1) =	1-P(F2=0)
P(G3=0) =	(P(I=1)P(HG3=1)+P(I=0)P(LG3=0))P(F2=0)P(G1=0)
P(G3=1) =	1-P(G3=0)

Table K.3: Probabilities for the random variables E1, F2, and G3 in EBN.

Appendix L

Tables for estimated probabilities and times

In this appendix, all the tables are of the same nature. The first two tables correspond to node H2, namely Tables L.1 and L.2, whereas the last two tables correspond to node H3. These tables are Table L.3 and L.4.

Random variable	Percentile value (or event)	Estimated value ± standard deviation for H2 in the BN	Estimated value ± standard deviation for H2 in the EBN
A1	0.789	0.306±0.234	0.269±0.206
A1	0.79868	0.301±0.235	0.267±0.207
A1	0.80403	0.298±0.236	0.266±0.207
A2	0.78909	0.307±0.233	0.269±0.206
A2	0.79862	0.301±0.235	0.267±0.206
A2	0.80406	0.298±0.236	0.267±0.206
B1	0 (event)	0.297±0.236	0.266±0.207
B1	1 (event)	0.313±0.232	0.271±0.206
C1	0 (event)	0.279±0.202	0.263±0.203
C1	1 (event)	0.88±0.1	0.39±0.261
D2	1.578E-7	0.297±0.368	0.266±0.207
D2	0.003276	0.298±0.236	0.266±0.207
D2	0.008035	0.299±0.235	0.271±0.206
E2	1.2660E-5	0.272±0.241	0.25±0.21
E2	0.003971	0.278±0.239	0.253±0.209
E2	0.06053	0.361±0.212	0.302±0.196
F1	0.0004197	0.28±0.24	0.244±0.21
F1	0.02614	0.284±0.238	0.249±0.208
F1	0.1354	0.364±0.211	0.333±0.185
G1	1.2350E-5	0.161±0.17	0.12±0.0893
G1	0.01132	0.171±0.169	0.13±0.0883
G1	0.5432	0.617±0.078	0.598±0.0408
G2	9.8820E-8	0.269±0.241	0.233±0.21
G2	0.003611	0.272±0.24	0.236±0.21
G2	0.1507	0.353±0.213	0.321±0.186
I	0 (event)	-	0.261±0.204
I	1 (event)	-	0.273±0.209
LE1	1.223E-6	-	0.266±0.207
LE1	0.005839	-	0.266±0.207
LE1	0.1746	-	0.27±0.206
HE1	0.006145	-	0.26±0.204
HE1	0.1129	-	0.263±0.203
HE1	0.9322	-	0.282±0.218

Table L.1: Part 1: Conditional results for H2. The first column represents the conditional random variable and in the second column, the percentile value or event. The third column shows the estimated value ± standard deviation for H2. At last, the fourth column displays the estimated value ± standard deviation for H2 in the EBN.

Random variable	Percentile value (or event)	Estimated value ± standard deviation for H2 in the BN	Estimated value ± standard deviation for H2 in the EBN
LF2	2.105E-11	-	0.267±0.207
LF2	6.3010E-7	-	0.267±0.207
LF2	0.04974	-	0.267±0.207
HF2	3.477E-6	-	0.267±0.207
HF2	0.01499	-	0.267±0.207
HF2	0.1807	-	0.267±0.207
LG3	7.0856E-7	-	0.267±0.207
LG3	0.04122	-	0.267±0.207
LG3	0.4744	-	0.267±0.207
HG3	0.001	-	0.267±0.207
HG3	0.01397	-	0.267±0.207
HG3	0.7172	-	0.267±0.207

Table L.2: Part 2: Conditional results for H2. The first column represents the conditional random variable and in the second column, the percentile value or event. The third column shows the estimated value ± standard deviation for H2. At last, the fourth column displays the estimated value ± standard deviation for H2 in the EBN.

Random variable	Percentile value (or event)	Estimated time ± standard deviation for H3, in hours, in the BN	Estimated time ± standard deviation for H3, in hours, in the EBN
A1	0.789	122±621	55.3±189
A1	0.79868	122±621	55.1±189
A1	0.80403	121±621	54.9±189
A2	0.78909	123±621	55.4±189
A2	0.79862	122±621	55±189
A2	0.80406	121±621	54.9±189
B1	0 (Event)	121±621	54.8±189
B1	1 (Event)	124±621	55.7±189
C1	0 (Event)	52.6±148	50±144
C1	1 (Event)	2.31E+3±2.64E+3	231±761
D2	1.5780E-7	121±621	54.8±189
D2	0.003276	121±621	54.8±189
D2	0.08035	121±621	55.9±189
E2	1.2660E-5	117±618	53.3±187
E2	0.0039715	118±618	53.6±188
E2	0.06053	132±629	59±192
NE2	0.3241	121±621	54.8±189
NE2	7.351	121±621	54.9±189
NE2	46.28	122±621	55.7±189
F1	0.02	119±621	52.8±187
F1	0.02614	120±621	53.2±187
F1	0.1354	128±623	61.8±195
NF1	0.2824	121±621	54.6±189
NF1	3.421	122±621	54.9±189
NF1	12.68	122±621	55.7±189
G1	1.235E-5	83±606	17.3±129
G1	0.01132	83.5±606	17.8±130
G1	0.5432	227±641	157±233
NG1	0.3343	94.7±612	29.1156
NG1	5.4	109±614	43±165
NG1	25.04	165±642	97.2±246
G2	9.88E-8	96.4±606	31.7±151
G2	0.003611	96.5±606	31.9±151
G2	0.11507	154±630	85±199
NG2	0.02458	97.4±606	32.7±152
NG2	3.452	97.8±606	33.2±152
NG2	560.4	174±650	104±247

Table L.3: Part 1: Conditional results for H3. The first column represents the conditional random variable and in the second column, the percentile value or event. The third column shows the estimated value ± standard deviation for H3. At last, the fourth column displays the estimated value ± standard deviation for H3 in the EBN.

Random variable	Percentile value (or event)	Estimated time ± standard deviation for H3, in hours, in the BN	Estimated time ± standard deviation for H3, in hours, in the EBN
NE1	0.6266	55.1±153	50.2±145
NE1	7.962	68.8±179	51.3±146
NE1	110.3	261±1.16E+3	66.5±289
NF2	0.1602	121±619	55.1±189
NF2	6.868	121±619	55.1±189
NF2	1426	124±628	55.1±189
NG3	0.5033	122±621	55.1±189
NG3	3.234	122±621	55.1±189
NG3	24.17	122±621	55.1±189
NH1	0.3559	122±621	55.1±189
NH1	3.987	122±621	55.1±189
NH1	12.79	122±621	55.1±189
I	0 (event)	-	49.7±144
I	1 (event)	-	61.3±244
LE1	1.223E-6	-	54.9±189
LE1	0.005839	-	54.9±189
LE1	0.1746	-	55.6±189
HE1	0.006145	-	49.6±144
HE1	0.1129	-	49.9±144
HE1	0.9322	-	79.8±382
LF2	2.105E-11	-	55.1±189
LF2	6.3010E-7	-	55.1±189
LF2	0.04974	-	55.1±189
HF2	3.477E-6	-	55.1±189
HF2	0.01499	-	55.1±189
HF2	0.1807	-	55.1±189
LG3	7.0856E-7	-	55.1±189
LG3	0.04122	-	55.1±189
LG3	0.4744	-	55.1±189
HG3	0.001	-	55.1±189
HG3	0.01397	-	55.1±189
HG3	0.7172	-	55.1±189

Table L.4: Part 2: Conditional results for H3. The first column represents the conditional random variable and in the second column, the percentile value or event. The third column shows the estimated value ± standard deviation for H3. At last, the fourth column displays the estimated value ± standard deviation for H3 in the EBN.