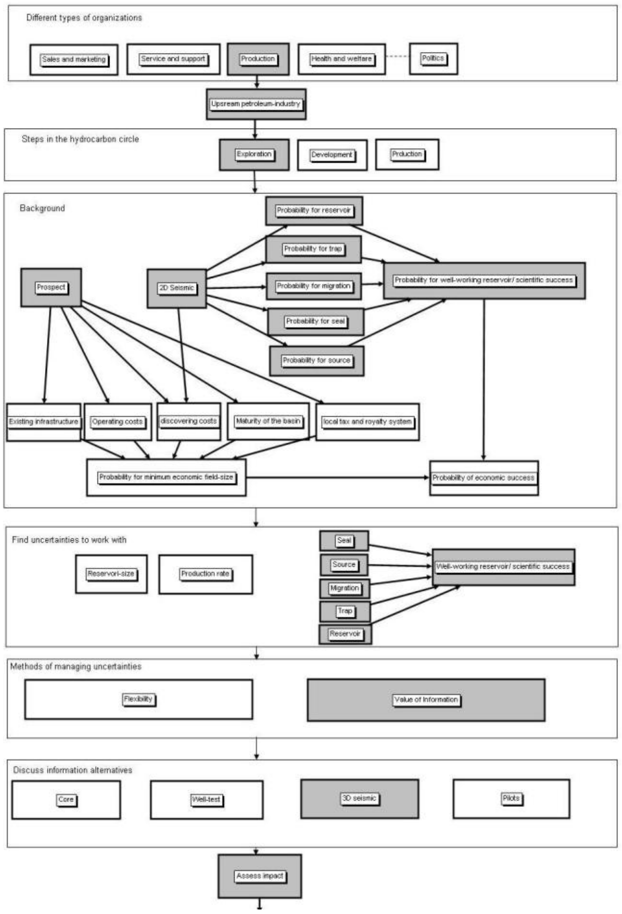
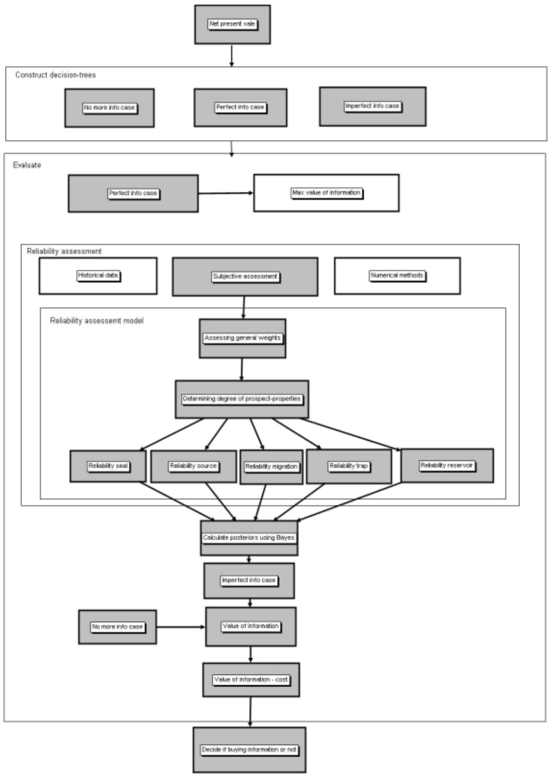
Master-thesis in Petroleum Engineering Management

# Value of Information
# Reliability of 3D Reflection Seismology in Exploration





Written by Hege Dybvig Andersen, June 2007

for ConocoPhillips and UoS

The man, who insists upon seeing with perfect clearness before he decides, never decides.

**Frederic Amiel**

# Summary

Decision makers who face uncertain prospects often gather information with the intention of reducing uncertainty. If we can reduce uncertainty about future outcomes, then we can make choices that give us a better chance at a good outcome. At least it is so in a perfect world where information is free and indicates the outcome of the uncertain event with certainty.

In the real world business nothing comes for free and information has a cost. Therefore we should investigate the benefits of the new information before spending time and money to collect it.

Value of information, VoI, is a decision-analytic tool used for this purpose. Schlafer (1959) was the first to discuss it in a general context and Grayson (1960) applied it to the oil-and gas industry. It has grown in use during the last years.

In this work the VoI-concept is described with emphasis on the question of shooting a 3D seismic-survey before drilling a wildcat or not. This is a question often encountered in the petroleum-industry.

The different steps in the working-process are described and Bayes' Theorem is introduced for probability updating. The reliabilities needed in this calculation and how to assess them is the main part of this work. An overview of how this is done in previous publications is made, and the different approaches are discussed.

Then a model is developed to aid in the assessment of reliabilities for seismic data gathering. The model is closely linked to the data acquired in the 3D seismic survey and to the properties of the actual prospect. The reliability assessment-model is subjective, but let the experts express their knowledge through weights and the degree of presence of prospect-properties instead of probabilities. This is directly related to their professional and technical skills. Probability is not.

# Content

# 1. Introduction

## 1.1 Background

In the petroleum-industry, we sometimes have the opportunity to purchase additional information to better define the value and uncertainty associated with important decisions.

Value of information, VoI, is a decision-analytic tool introduced by Grayson (1960) to the petroleum-industry in the late 1950's and has grown in use during the last years.

To make better decisions it is important to assess the input values to this model as well as possible. One of the input values is the reliability, or information accuracy, on which the focus of this work will be.

## 1.2 Purpose

Based on the literature, different approaches for how to come up with a reliability-value will be described.

An alternative method is also developed in an attempt to make the assessment in the best possible way. What is meant by the term "best possible way" is explained in chapter 3.

## 1.3 Overview

First the Value of information concept is introduced. The theory is explained using an example where an oil-company has to decide whether or not to shoot 3D seismic before drilling a wildcat.

A general methodology for the analysis is developed and Bayes' Theorem is introduced for use in calculations.

Then there is a brief discussion on reliability and why it is an important input value. This is followed by an overview of how reliability-assessments are treated in the literature and examples of these methods.

An alternative way for reliability-assessment is developed for 3D seismic in exploration.

In the developing-process the basic theory of reflection seismology is explained. Relationships between acquired data and geological features required for the formation of hydrocarbon reservoirs are also developed. The reliability assessment model builds on these relations.

The assumptions made for developing the model are listed. Also benefits and constrains using the model is described, and suggestions for how to develop it are given.

## The topics in a bigger context

The figure on the two following two pages, which is also used as an illustration on the front-page, gives an overview of this work. It describes the relationships between the different topics and puts them into a bigger context. The topics discussed in this work are illustrated with grey boxes.

The figure indicates that decision analysis can be used in all types of organizations. Here we focus on the upstream petroleum-industry which is categorized as a production organization. The focus will be on the exploration phase.

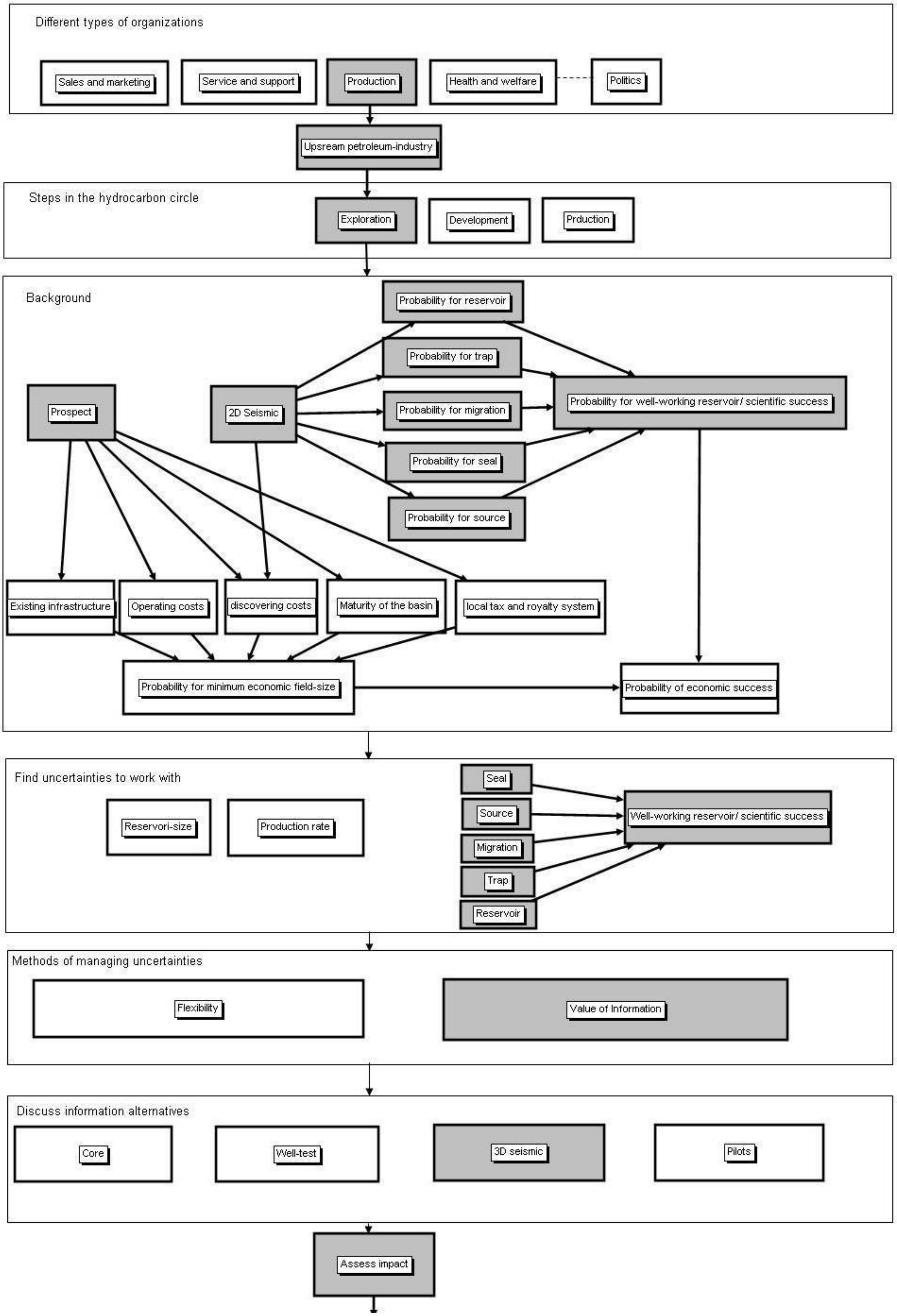
We have got a prospect on hand and the information about it is based on 2D seismic. This helps us assess prior probabilities for scientific success and for minimum economic field size. In this work I will concentrate on the probability of scientific success.

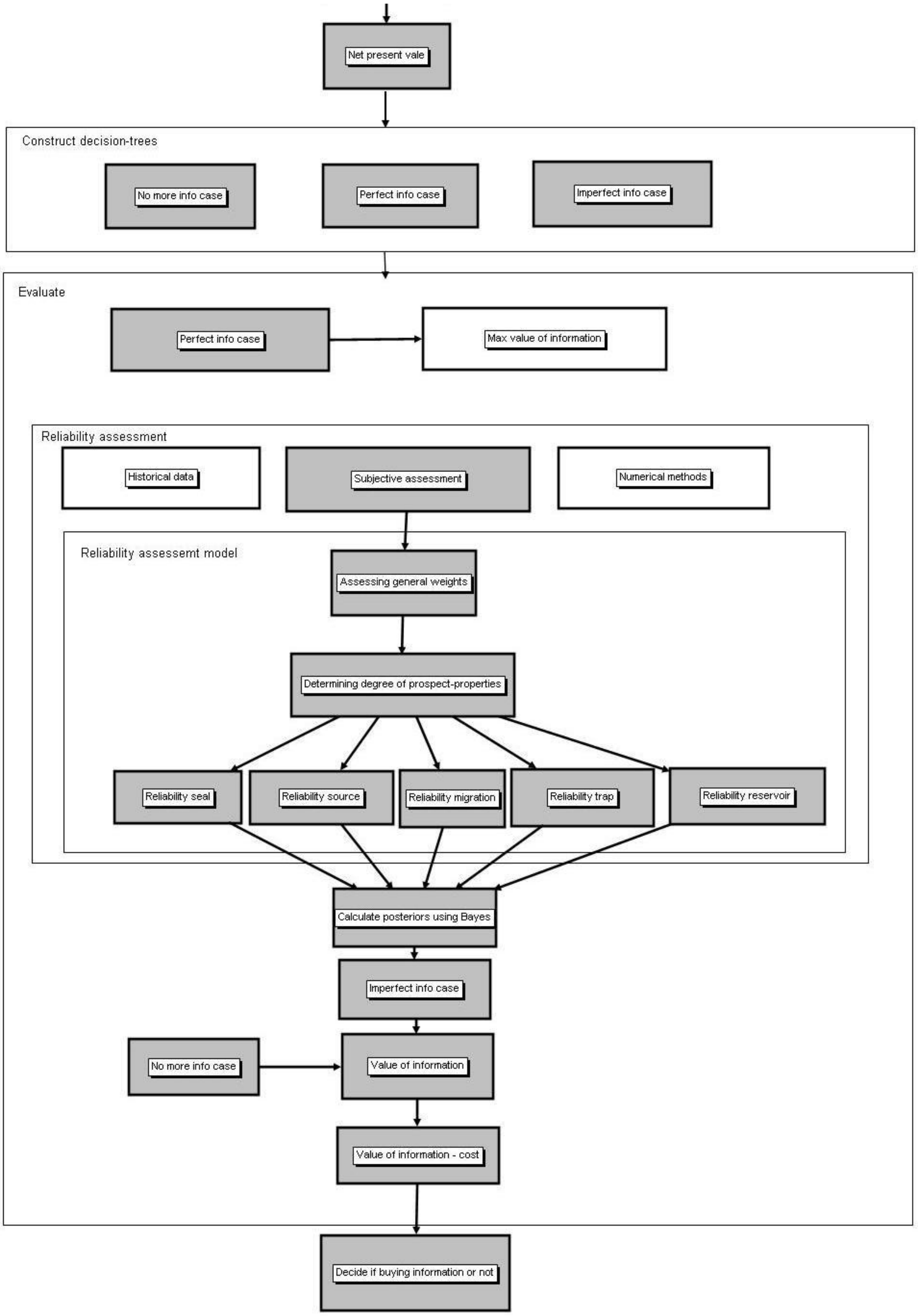
To manage the uncertainty associated with the prospect, flexibility or VoI can be used. Here the focus will be on VoI, and the remaining part of the figure is based on the methodology of the VoI- analysis.

The information-source we will use is 3D seismic. We now construct decision-trees for the no more information case, the perfect information case and the imperfect information case and evaluate each of these.

When evaluating the imperfect information case we will need the reliability of 3D seismic. This is found by subjective assessment using the reliability assessment model developed in this work.

Then the value of information is calculated. This will in turn help us deciding whether or not to shoot 3D seismic.


Different types of organizations
Sales and marketing
Service and support
Production
Health and welfare
Politics
Upsream petroleum-industry
Steps in the hydrocarbon circle
Exploration
Development
Prduction
Background
Probability for reservoir
Probability for trap
Probability for migration
Probability for seal
Probability for source
Prospect
2D Seismic
Probability for well-working reservoir/ scientific success
Existing infrastructure
Operating costs
discovering costs
Maturity of the basin
local tax and royalty system
Probability for minimum economic field-size
Probability of economic success
Find uncertainties to work with
Reservori-size
Production rate
Seal
Source
Migration
Trap
Reservoir
Well-working reservoir/ scientific success
Methods of managing uncertainties
Flexibility
Value of Information
Discuss information alternatives
Core
Well-test
3D seismic
Pilots
Assess impact


Net present vale
Construct decision-trees
No more info case
Perfect info case
Imperfect info case
Evaluate
Perfect info case
Max value of information
Reliability assessment
Historical data
Subjective assessment
Numerical methods
Reliability assessemt model
Assessing general weights
Determining degree of prospect-properties
Reliability seal
Reliability source
Reliability migration
Reliability trap
Reliability reservoir
Calculate posteriors using Bayes
Imperfect info case
No more info case
Value of information
Value of information - cost
Decide if buying information or not

# 2. Literature review

A number of books provide general overviews of the VoI -concept. An example is Clemen and Reilly (2001).

The ideas are discussed further in several articles and are illustrated in relation to information-sources such as 3D- and 4D seismic, observation-wells, logging-tools and oil-prize forecasts. An overview of many of these articles is included in appendix A.

Both Leach et al. (2007) and Coopersmith, Cunningham (2002) point out 3 things VoI depends on. This is the degree of uncertainty, economic impact and the reliability of the information-source.

Koninx (2000) points out that full life-circle analysis is required for a good value of information analysis. Also Coopersmith and Cunningham (2002) have suggestions for a best approach to this work.

Even though the concept has grown in use during the last years, Begg et al. (2002) remind us of that VoI is not the only way to manage uncertainty.

Schlafer (1959) was the first to discuss VoI in a general context and Grayson (1960) applied it to the oil-and gas industry in 1960. Grayson is one of the authors using historical data when assessing reliability. Grayson emphasizes that although probability assignments have been equated with past frequencies in his example, an operator does not have to do that. Instead the decision maker or the geologist can leverage his own experience, judgement or information in order to assign personal probabilities. This is done in Coopersmith et al. (2006).

In an attempt to make the reliability assessment more objective Bickel et al. (2006) link seismic accuracy assessment to observable seismic data. The relations are based on Perturbation theory and simulations.

The reliability assessment model developed in this work is inspired by Coopersmith et al. (2006) and is partly based on the 9 questions suggested to counteract biases and consider relevant objective data.

The model emphasises on seismic-information, and it is important to be aware of the role of, and the requirement to 3D seismic is different at each stage of the hydrocarbon cycle as discussed by Ritchie (1986).

The conceptual way to describe the value of information illustrated by Head (1999) is adopted.

To understand how 3D seismic data are collected and processed the geophysical introductory book by Mussett and Khan (2000) was of use. Also Freedman and Young (2000) and came in handy.

When looking for ways of expanding the model there is much geophysical literature available. Thore et al. (2001) describes the seismic workflow in greater detail and explain how each step of the seismic processing chain has inherent uncertainty that can be evaluated.

Houck (2004) and Bickel et al. (2006) discuss how reliability can be improved and that this often will result in increased costs. Lansley (1999) explain these different techniques for a better image.

# 3. Problem definition

Because data-accuracy or reliability is such an important input to the VoI-calculations it is useful to examine how this can be done in the best possible way.

By the term “best possible way” is here meant:

1) The reliability assessment is made focusing on the project on hand. That means that the assessment method is not to general.
2) The reliability assessment is as objective as possible. This means that the value is not too sensitive to the person who assesses it.
3) There are standard procedures to follow and these are not to cumbersome.
4) The people who assess the reliability use his or her professional and technical skills.

Reliability is closely connected to the information-source and therefore it is useful to do this examination based on one particular information-source.

In this work the focus is on 3D reflection seismology. This is because seismology is used in the whole up-stream hydrocarbon-circle from exploration to production. It is also a very costly information-source and its value should be justified prior to applying these expenditures.

The role of, and the requirement to 3D seismic is different at each stage of the hydrocarbon cycle. I will focus on the exploration phase.

The problem in this work is then defines as

Value of information
-Reliability of 3D Reflection Seismology in Exploration

# 4. Value of Information, VoI

## 4.1 General

Information has a cost and therefore we should investigate the benefits of the new information before spending time and money to collect it. VoI is a decision-analytic tool for this use, first discussed by Schlafer (1959) in a general context, and introduced to the petroleum-industry by Grayson (1960).

Both in the work by Leach et al.(2007) and Coopersmith, Cunningham (2002) the authors point out that in general the value of gathering information depends on

1) The degree of uncertainty we are facing. There is no use in collecting additional data, if we are almost sure about the outcome anyway. This is the prior probability.
2) How big the economic impact of the decision is. If a bad outcome of the project would hurt the company seriously economically, then information about project outcome is valuable. This is the net present value, NPV.
3) How reliable the information is. That is how well it predicts the true outcome. It is no use in collecting data which would guide us to wrong decisions. These are the conditional probabilities or reliabilities.

## 4.2 VoI in the petroleum-industry

In the petroleum-industry we face decisions regarding buying 3D seismic, taking cores, designing well-tests and pilots. The aim is to determine if it is valuable to do so, before making large investment-decisions. We estimate the value of the information we might acquire, before knowing what it might tells us.

## 3D seismic

An example of this kind of value estimation is if we should drill a wildcat. There is a chance for the well to be dry and we will loose money.

Should we shoot 3D-seismic to get a clearer view of what is underground, and let this help us separate good projects from bad ones before drilling? Or should we just stick to the 2D seismic we have already got?

If the 3D-seismic says it is most likely not to be a well working reservoir. Then we will not drill and not loose money by drilling a dry hole. But the 3D- seismic has a cost and there is a chance that what the seismic tells is wrong. In this case we can miss a well-working reservoir.

This situation is illustrated in the decision-tree in figure 1. It is a chronological overview of the decisions we are facing and the uncertainties associated with them. The factors influencing the VoI are also included in the figure:

1) The degree of uncertainty is represented with the probability P (economic success). This is based on the data we already got, among other things 2D-seismic.
2) The economic impact is represented with the blue net preset values, NPV.
3) The reliabilities of the information is not directly shown in the figure, but are used to calculate the four probabilities
   P (economic success| "economic success")
   P (economic failure | "economic success")
   P (economic success| "economic failure")
   P (economic failure | "economic failure")

The upper branch of the decision tree includes an alternative to acquire additional information. Analysing this option follows a definite series of steps:

1) We purchase the 3D seismic
2) We learn the measurements and other details it tells us
3) The decision-maker decides how to proceed
4) Having decided on a strategy, the actual state of nature will appear if we drill a well.

This is a general pattern and the analysis of decisions to purchase imperfect information will always in follow this.

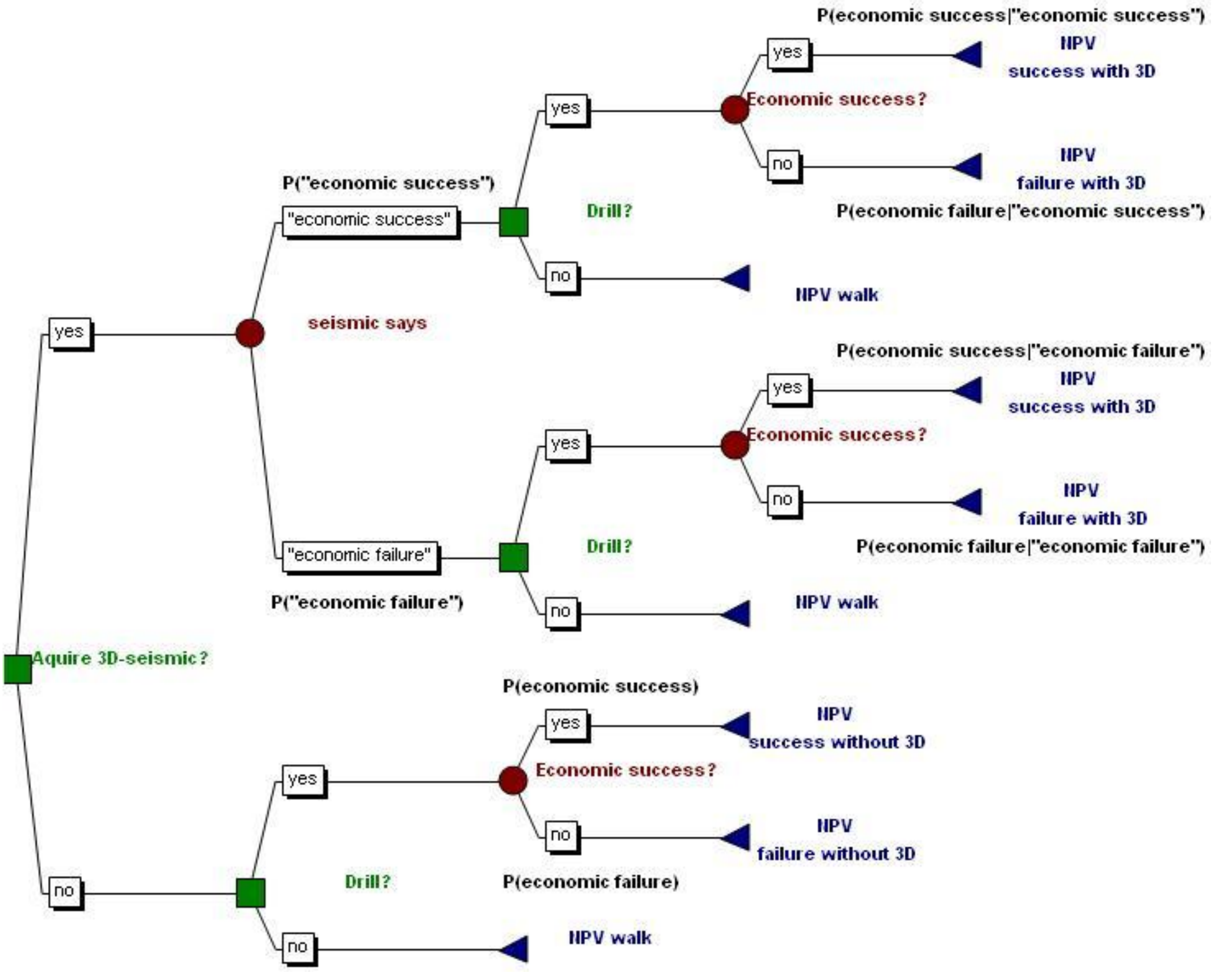


**Figure1. VoI decision-tree for 3D Seismic example**

If we assume that the company is risk neutral and seek to maximise the expected NPV, or that they have an exponential utility function, the VoI is essentially an expected monetary value, EMV, calculation.

We analyze the expected benefit of series of actions and outcomes either with or without the proposed data being available. The difference in EMV between the scenario with additional information and the one without is then the value of the data acquired.

Value-of-Information = Asset Value $_{\text{with information}}$ – Asset Value $_{\text{without information}}$

This expression is given in much of the literature on VoI. An example is Coopersmith and Cunningham (2002)

Because value of information is defined not to be negative the definition may be re-written:

$$\text{Value-of-Information} = \max(\text{Asset Value}_{\text{with information}} - \text{Asset Value}_{\text{without information}},\ 0) \quad (1)$$

The expected benefit has to be traded-off against the cost of information in order to obtain the net gain from information. If this is a negative quantity, it means that the information is not worthwhile in cost-benefit terms.

The monetary return on the investment of data acquisition is usually several years in the future. Therefore there are uncertainties associated with these. The longer the timeframe between data-gathering and payback (development), the bigger the uncertainties and the more difficult the VoI-analysis is. This is discussed by Coopersmith et al. (2006)

In the 3D seismic example, a survey not only distinguishes high risk from low risk locations, but might have impact on production performance. This is because it supports us when finding the optimal positions of development wells, enhancing recovery per well and reducing cost per barrel which is discussed by Varela and Lake (2002). The 3D survey could also find completely new, previous unknown, low risk locations. This would off course also impact the payoff.

Early in the exploration phase of an area, data is generally valuable since so many options for development are still open and therefore there are many ways in which the seismic may improve the outcome. This means that $NPV_{\text{success with 3D}}$ often exceed $NPV_{\text{success without 3D}}$

A good analysis therefore require a full-life cycle analysis, and inputs from many different disciplines such as geoscientists, petroleum engineers, surface engineers and economists. Looked at from this point of view, it is a scrutiny about where data adds value in the life cycle of exploration and production. It gives us a better understanding of the business and this will lead to value-optimisation and creation. This is discussed by Koninx (2000)

We do not collect information if there is not a decision which could be changed as a result of it. As in the seismic example, we are to decide to drill a well or not. This is an important fact to remember especially in the oil and gas industry where lots of data are available. We are often offered to buy technology to help us collect data, but it is not the data itself that is valuable, it is the decision they support that counts.

The upper limit for what the information is worth for the company and how much they maximum are willing to pay for it, is the value of perfect information. This is information that always will predict the true state of nature. No information in the real world is that reliable, this is highest quality but sure we would not spend more money on lower quality data than we would on this.

It is also important to know that buying information is not the only way of reducing uncertainty. The value of flexibility discussed by Begg et al. (2002) is another approach. It takes into account the value that can be achieved by using flexibility to manage uncertainty.

## 4.3 Methodology for VoI- analysis

It is important to design a consistent, mathematically rigorous and quality controlled approach to the VoI- analysis. If this is done properly, only a few well-defined input assumptions are needed.

Based on the work by Koninx (2000), and Coopersmith, Cunningham (2002) the working-process is summarized into the following 9 steps. This is illustrated in figure 1.

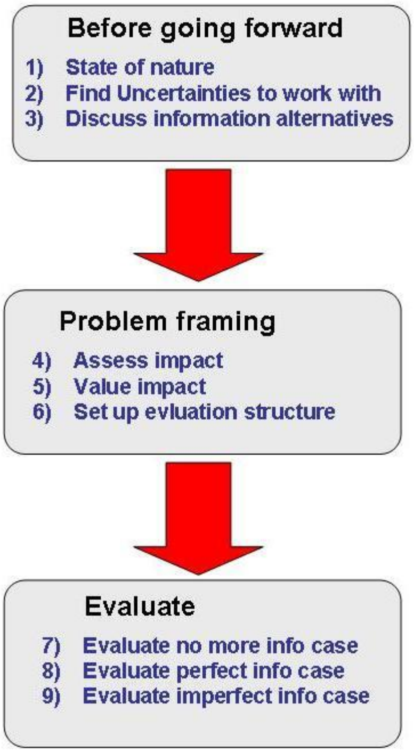


**Figure 1. Methodology for Value of Information analysis**

The different steps are described below.

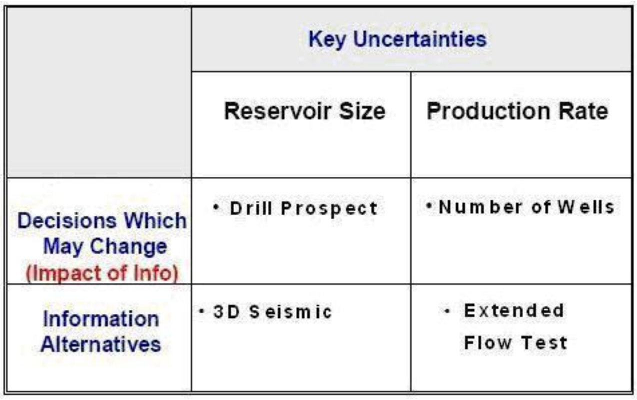
## Before going forward

It is important to know the "no more info" case. What are the uncertainties, and what stops the decision from being made now?

1) Prior Probability.
   The degree of uncertainty we are facing right now. This is the underlying uncertainty, the state of nature. In our example it is how certain we are about an economic success, based on the 2D-seismic. In figure 1 this is the P (economic success).

2) Find uncertainties to work with
   Use sensitivity analysis to identify the variables with the largest potential to affect value. These also have the highest potential to add value, given they can be resolved, reduced or avoided. Gathering information on these variables can be worthwhile.

3) Discuss information alternatives.
   This step utilizes a so-called "VoI uncertainty" table. Here we list all of the key uncertainties in the decision problem, the associated decisions which could change and the relevant information alternatives.
   Figure 2 is based on Coopersmith and Cunningham (2002).



| | Key Uncertainties | |
|---|---|---|
| | Reservoir Size | Production Rate |
| Decisions Which May Change (Impact of Info) | • Drill Prospect | • Number of Wells |
| Information Alternatives | • 3D Seismic | • Extended Flow Test |

**Figure 2. VoI uncertainty table**

## Problem framing

Isolate and evaluate the benefit of obtaining information on one uncertainty at a time.

4) Assess impact.
   Identify the impact that the requested data could have. Where does it influence decisions taken in the future and how does this impact change under different scenarios?

   This is the most time-consuming part a good VoI-analysis and it requires teamwork of the subsurface with the facilities engineers and economists.

5) Value impact.
   This means quantifying the monetary impact on the bottom-line of the various combinations of uncertain outcomes and options.
   This is the $\text{NPV}_{\text{Economic success}}$, $\text{NPV}_{\text{Economic failure}}$ and $\text{NPV}_{\text{Walk}}$ in figure 1.
   This step also requires a multi-disciplinary approach.

6) Set up the evaluation structure
   Here we have to understand the anatomy of the decision problem. Decision-trees are useful tools and are used to represent the timeline in the decision.
   a) Set up the decision-tree for no more information case. This is the lower branch of the decision tree in figure 1.
   b) Set up the decision-tree for perfect information case. This is the upper branch of the decision-tree in figure 1
   c) Set up the decision-tree for imperfect information case. The structure is analogue to the perfect information case.

## Evaluate

In calculating the EMV's, we will need some basic probability theory. Here just a brief introduction to probability is given, and the form of Bays Theorem that we will need for the imperfect information case is introduced. Parts of this discussion are based on J. Joyce (2003) and Walpole (2002).

## Bayes' Theorem

The set of all possible outcomes of a statistical experiment, or a chance-node in our decision-tree, is called the sample space and is represented by the symbol S.

If we are interested in the number that shows on the top-side when tossing a dice, the sample-space would be S = {1, 2, 3, 4, 5, 6}

An event is a subspace of a sample-space. We may be interested if the outcome when a dice is tossed is divisible by 3. This will occur if the outcome is one the subset A= {3, 6}. Another event B may be if the outcome is 6. B= {6}

The relationship between events and the corresponding sample-space can be illustrated graphically by means of Venn-diagrams. The dice-example may look like in the figure 3 below.

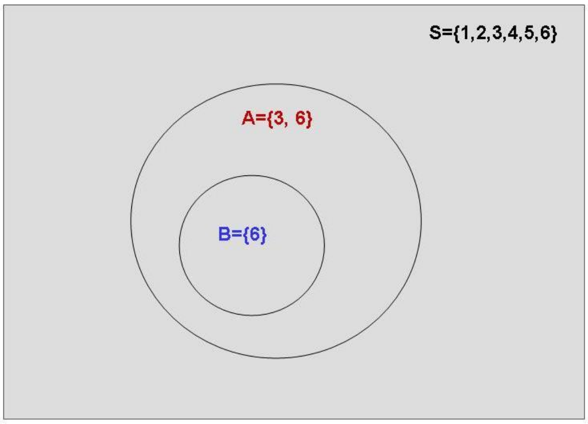


**Figure 3. Venn diagram**

The probability of event A is

$$P(A)=\frac{\text{number of outcomes corresponding to event A}}{\text{number of outcomes in the samplespace}}=\frac{\text{\# favourable}}{\text{\# possible}}=\frac{2}{6}=\frac{1}{3}$$

The probability of event B is

$$P(B)=\frac{1}{6}$$

The probability for both events to occur at the same time, the joint probability, is

$$P(A \cap B) = \frac{\text{number of outcomes corresponding to both events at the same time}}{\text{number of outcomes in the sample-space.}} = \frac{1}{6}$$

Often knowledge about the occurrence of one event, will change the probability for another. To illustrate this let us again consider tossing a dice.

The sample space is S={1,2,3,4,5,6}

Events A and B are defined as:

A=odd-number={1,3,5}

B=less than 4={1,2,3}

The probability for each of the events is:

$$\text{P(A)=} \frac{\text{number of outcomes corresponding to event A}}{\text{number of outcomes in the samplespace}} = \frac{\text{\# favourable}}{\text{\# possible}} = \frac{3}{6} = \frac{1}{2}$$

$$\text{P(B)=} \frac{\text{number of outcomes corresponding to event A}}{\text{number of outcomes in the samplespace}} = \frac{\text{\# favourable}}{\text{\# possible}} = \frac{3}{6} = \frac{1}{2}$$

The Venn-diagram for this situation is shown in Figure 4.

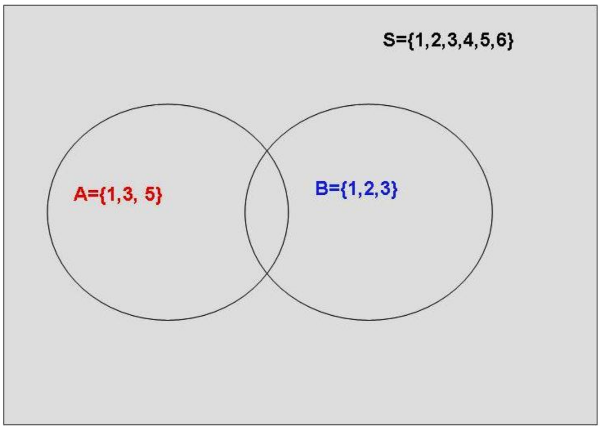


**Figure 4. Venn diagram Conditional probability**

But what is the probability for event A, if we know event B has already occurred? This is called the conditional probability and is written P(A|B).

We know that the outcome is less than 4, and then only 1 and 3 are possible odd-numbers.

The sample-space is reduced to

S=B={1,2,3}

The number of outcomes associated with event A is also reduced

A=odd-number={1,3}

The conditional probability is

$$P(A|B)= \frac{\text{number of outcomes corresponding to the new event A}}{\text{number of outcomes in the new samplespace}} = \frac{\text{\# favourable}}{\text{\# possible}} = \frac{2}{3}$$

Generally the conditional probabilities are defined as

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \quad \text{or} \quad P(B|A) = \frac{P(A \cap B)}{P(A)} \tag{2}$$

Solving the last expression with respect to $P(A \cap B)$ and substituting into the first, give us what we call Bayes' Theorem.

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{3}$$

If event $A_1$, $A_2$, …..$A_k$ constitute a partition of the sample-space S as illustrated in figure 5,

then $P(B) = P(A_1 \cap B) + P(A_2 \cap B) + ...P(A_k \cap B) = \sum_{i=1}^{k} P(A_i \cap B) = \sum_{i=1}^{k} P(A_i) \cdot P(B|A_i)$ (4)

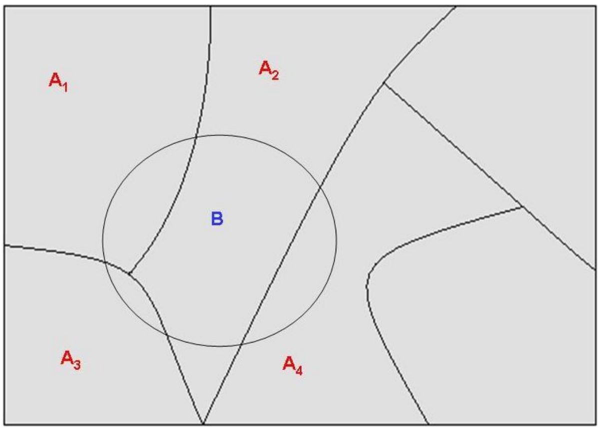


**Figure 5. Venn diagram. Partitioned sample-space**

This expression for P(B) substituted into equation (3) gives us Bayes' Theorem in the form we will need in our VoI-calculations:

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{\sum_{i=1}^{k} P(A_i) \cdot P(B|A_i)} \tag{5}$$

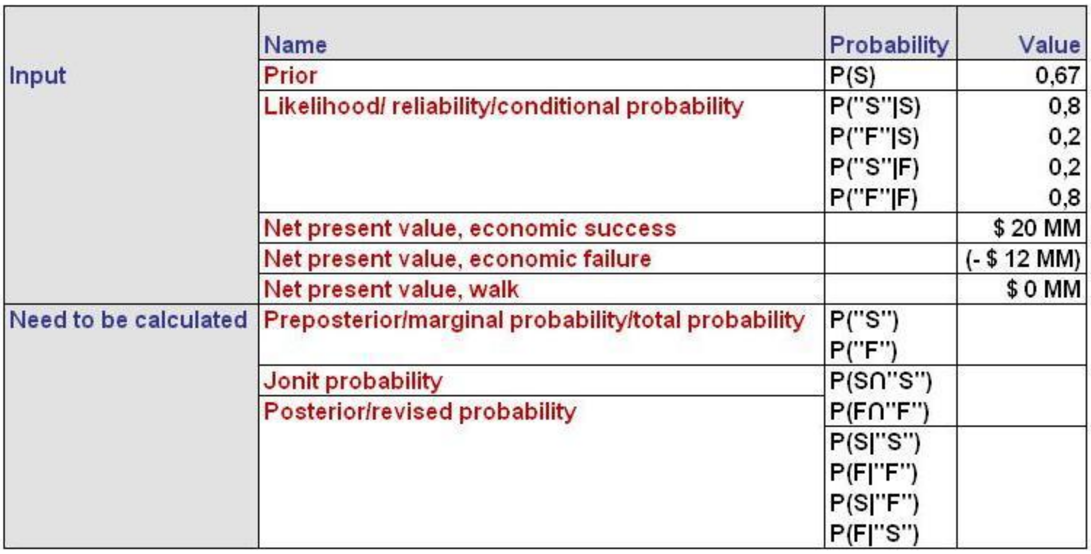
Now we are ready to evaluating the decision-trees.

In our wild-cat example illustrated in figure 1, let us assume that at a well-working reservoir is analogous to an economic success.
In the upper branch of decision-tree in figure 1, there are two uncertain chance-points, each associated with two outcomes or events.
In the lower part of the decision tree there are only one chance-node.
For short we will write S for economic success, and F for economic failure.

To illustrate how to calculate the VoI, it is convenient to put numbers to the different variables in figure 1. Table 1 shows input values, and the probabilities that need to be calculated.

The net present values are given in $ million (MM)

**Table 1. Input-values for VoI calculations**



| | Name | Probability | Value |
|---|---|---|---|
| Input | Prior | P(S) | 0,67 |
| | Likelihood/ reliability/conditional probability | P("S"\|S) | 0,8 |
| | | P("F"\|S) | 0,2 |
| | | P("S"\|F) | 0,2 |
| | | P("F"\|F) | 0,8 |
| | Net present value, economic success | | $ 20 MM |
| | Net present value, economic failure | | (- $ 12 MM) |
| | Net present value, walk | | $ 0 MM |
| Need to be calculated | Preposterior/marginal probability/total probability | P("S")<br>P("F") | |
| | Jonit probability | P(S∩"S")<br>P(F∩"F") | |
| | Posterior/revised probability | P(S\|"S")<br>P(F\|"F")<br>P(S\|"F")<br>P(F\|"S") | |

Figure 6 shows the decision-tree with these values incorporated, but before the posteriors are calculated.

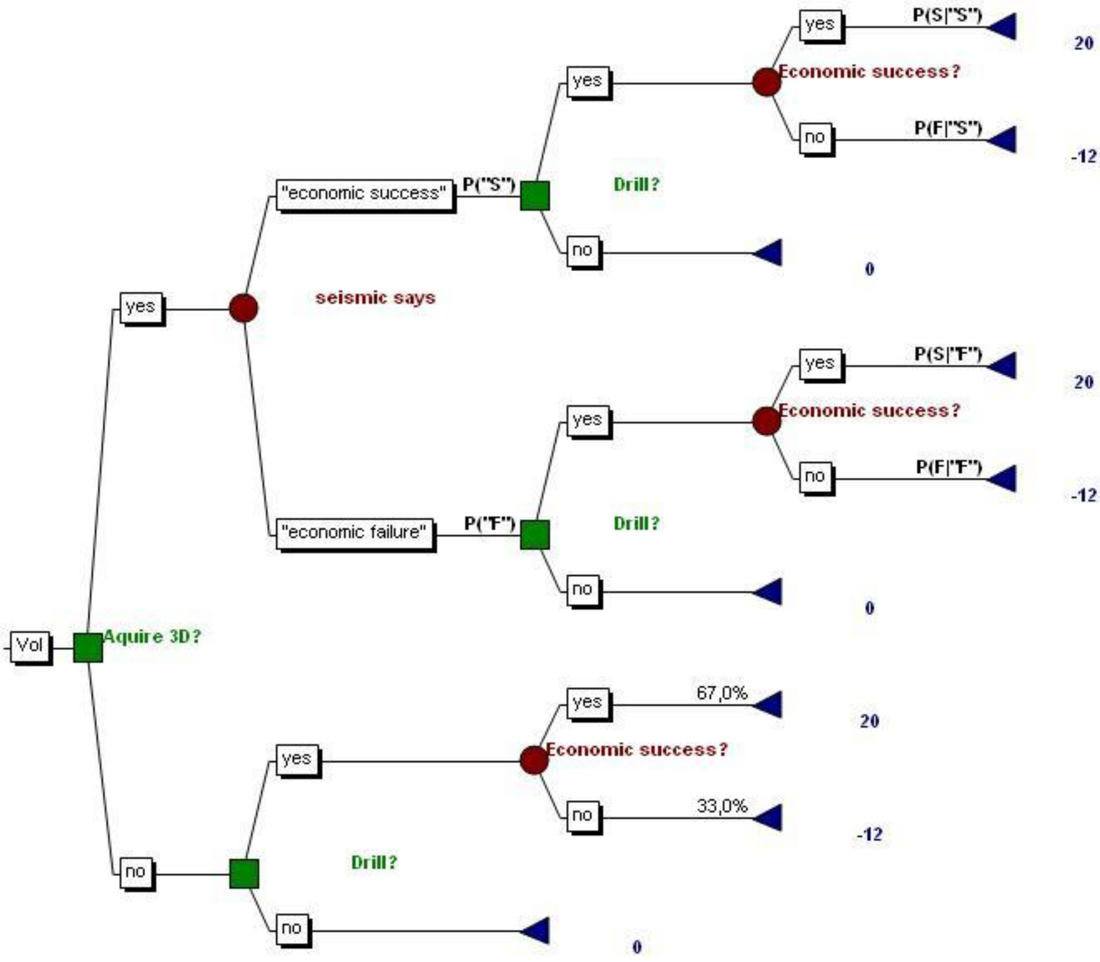


**Figure 6. Decision tree before posteriors are calculated**

7) Evaluate no more info case.

$\text{Asset-value}_{\text{without information}} = \text{EMV}_{\text{without information}}$

We have values needed to calculate the EMV in the lower branch of the decision-tree. If we assume the company is risk neutral and seeks to maximize the excepted NPV, then we calculate the EMV by starting rightmost, calculating the expected values in the chance-points(circles) and selecting the highest monetary value in all decision-points(squares)

Expected monetary value chance-point $0.67 \cdot 20 + 0.33(-12) = \$\ 9.44$ MM

Choosing \$ 9.44 MM in decision-point because \$ 9.44 MM > 0 MM

$\text{Asset-value}_{\text{without information}} = \text{EMV}_{\text{without information}} = \$\ 9.44$ MM

8) Evaluate perfect information case.

In the upper branch of the decision-tree we lack the posterior and the pre-posterior.

But because the information in this case always tells the true state of nature, the posteriors are P(S|"S") =P(F|"F")=1.

Because it never predicts wrong P(S|"F")=P(F|"S")=0

The pre-posterior is the denominator in Bayes' Theorem:

$$P(B) = P(A_1 \cap B) + P(A_2 \cap B) + ...P(A_k \cap B) = \sum_{i=1}^{k} P(A_i \cap B) = \sum_{i=1}^{k} P(A_i) \cdot P(B \mid A_i)$$

We calculate them as follows:

P("S")= $P("S" \mid S) \cdot P(S) + P("S" \mid "F") \cdot P(F) = 1 \cdot 0.67 + 0 \cdot 0.33 = 0.67$

P("F")=1-0.67=0.33

We have values needed to calculate the EMV in the upper branch of the decision-tree

EMV=Asset-value $_{\text{perfect information}}$= $0.67(1 \cdot 20 + 0 \cdot (-12)) + 0.33 \cdot 0 = \$\,13.44$ MM

Value-of-Perfect-information=13.44-9.44= $ 3 MM

9) Evaluate imperfect information case

The decision-tree looks the same as the one in the perfect information case, but the reliabilities have other values. In table 1 they are listed, so we will find the posterior using Bayes' Theorem. In real cases one of the difficulties using VoI- method, is to assess these reliabilities.

a) Assess reliabilities.

Chapter 5 and 6 are concerned about this.

b) Calculate the posterior probabilities needed.

Bayes' Theorem in general form:

$$P(A \mid B) = \frac{P(B \mid A) \cdot P(A)}{\sum_{i=1}^{k} P(A_i) \cdot P(B \mid A_i)}$$

Bayes' Theorem in this case:

$$P(S \mid "S") = \frac{P("S" \mid S) \cdot P(S)}{P("S")} = \frac{P("S" \mid S) \cdot P(S)}{P("S")}$$

$$= \frac{P("S"|S)\cdot P(S)}{P("S"|S)\cdot P(S)+P("S"|F)\cdot P(F)}$$

$$= \frac{0.8\cdot 0.67}{0.8\cdot 0,67+0.2\cdot(1-0.67)} = \frac{0.536}{0.6} = 0.89$$

and

$$P(F|"F") = \frac{P("F"|F)\cdot P(F)}{P("F"|F)\cdot P(F)+P("F"|S)\cdot P(S)} = \frac{0.8\cdot(1-0.67)}{0.8\cdot(1-0.67)+0.2\cdot 0.67} = \frac{0.264}{0.4} = 0.66$$

The last of the posteriors from one chance-node is simple to calculate.

$P(F|"S") = 1-P(S|"S") = 1-0,89 = 0,11$

$P(S|"F") = 1-P(F|"F") = 1-0,66 = 0,34$

Note that the pre-posterior are the denominator in Bayes' Theorem.

We have now all that we need to calculate the

EMV $_{\text{with information}}$ =Asset-value $_{\text{with information}}$

$= 0.6\cdot(0.89\cdot 20+0.11\cdot(-12))+0.4\cdot 0 =$ \$9.89 MM

Value of Information= Asset Value $_{\text{with information}}$ – Asset Value $_{\text{without information}}$

= 9. 89- 9. 44= \$ 0. 45MM

If the value of the information exceed its costs, then it is valuable to acquire it.

# 5. Reliability

## 5.1 Sensitivity of VoI to reliability

Reliability is also called likelihood, conditional probability or accuracy. As shown in the previous chapter, we need it to calculate the posteriors or revised probabilities in the decision-tree when calculating the VoI.

The reason we do not ask for the posteriors right away is that it is easier to assess how much we actually trust that the information predict the true state of nature, than the probability for the state of nature to be what the information-source tells.

The information-gathering actually work this way as well. The information-source tries to indicate what the state of nature is. The reliability is an expression for how correct the information source predict the actually outcome of an uncertain event.

Reliability is an important input value in VoI- calculations and often even a small change in the reliability-value, results in a different decision on information collection.

This is best illustrated by a sensitivity analysis of the 3D-seismic example above.
Figure 7 illustrates the VoI as a function of reliability P("S"|S)

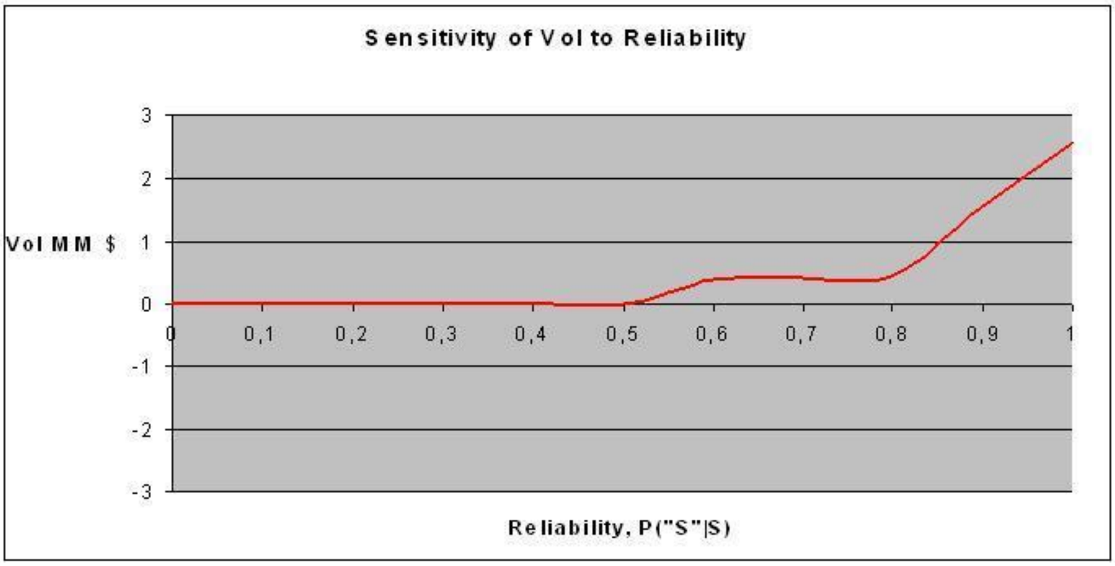


**Figure 7. Sensitivity of VoI to reliability**

The reliability is 0.5 when the value of the information is zero. This is logically because then it is as likely that the information give the right state of nature, than that it does not. The information adds no value.

When the reliability is 0.6, then the value of information is almost $ 0.38 MM. If the cost of the information is lower than this, it is worth gathering this information.

When the reliability increases from about 0.8 to 0.9 the VoI increases from $ 0.46 MM to $ 1.56 MM. If the cost of the information is somewhere between these two values, then a difference in reliability of 10 % will change the decision from not gather, to gather information.

To really show how critical the reliability can be in such a case, we can use an example where the cost of the information is $ 470 000. The sensitivity-analysis shows that the data is worth buying if the reliability is 81 percent, but not when it is 80 percent.

In chapter 4, the reliabilities are given in table 1, and we just have to calculate the posterior or revised probabilities, using Bayes' Theorem. This is not the case in real decisions. One has to come up with these values in one way or another. If we in the case above think that the reliability of the information is around 80% and the cost $ 470 000, then it is worth making an effort in assessing the reliability as correct as possible. Data acquisition decision should be robust given the uncertainties in the reliability.

## *5.2 Reliability assessment in the literature*

There are different methods used to assess reliability in VoI calculations. Appendix A, gives an overview of 37 publications. These cover the most common methods for reliability assessment.

Papers using a real option approach are not included, because these papers are not concerned with reliability and Bayes' Theorem.

In previous published work there are roughly 8 different ways of treating reliability. The first 5 groups make up 70% of the total number of articles examined. In none of these groups the authors explicitly assess reliabilities.

The different approaches are described below:

### No assessment (27 publications)

In the literature there are 5 different approaches to avoid explicit reliability assessment

1) Uncertainties are reduced by acquiring information. The posteriors are given without any use of Bayes' Theorem.

2) Reliabilities are given. No discussion on how to assess them.

3) Assume perfect information and set the reliabilities to 1.

4) No direct mentioning of reliabilities. However, there are comments indicating that they are aware of probability updating.

5) A general discussion of the concept VoI, but reliabilities are not mentioned.

## Reliabilities assessed (10 publications)

In the four groups below the red line in the table in appendix A, the authors have assessed the reliability. The three different approaches are described in the following.

## Historical data

To illustrate this method I will use (Grayson 1960). He uses as an example the decision of whether or not to purchase seismic information.

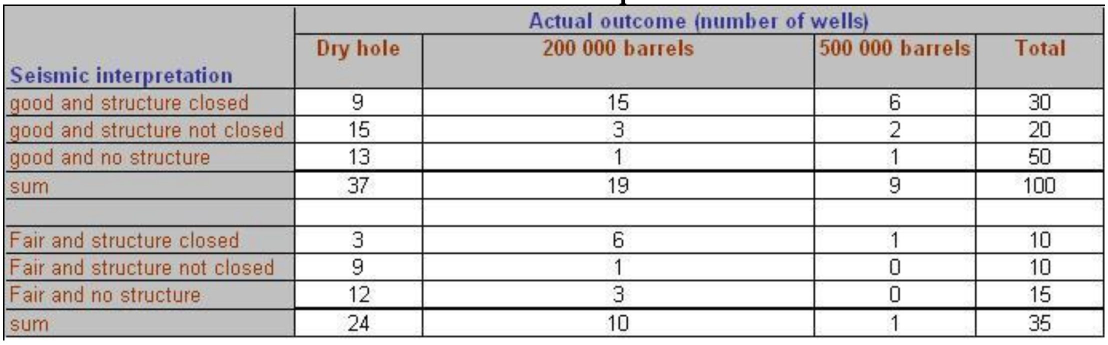
The author splits the reliability into two parts, he does not explicit say so, but he says that if seismic is bought, the decision maker will not receive information that will definitely predict whether or not oil and gas is underground. He receives seismic reflections that indicate, with various degree of imperfection the probable underground contours of various geologic horizons. This is called the tool or information accuracy.

One of the most favourable spots for the accumulation of oil and gas is a closed structure. Thus seismic information is valuable mainly for the reason of indicating whether it is likely that a structure exists, and if so, whether it is likely to be closed. This is the interpretation accuracy.

The reliabilities are found using historical information and the author stresses that this is done only when the decision maker makes the assumption that the future will be similar to the past. In this case he equates past frequencies with the current probability assignments.

Grayson then gives a table showing how analyzing statistics for seismic shoots in a particular geological area may look like. Table 2 shows the actual frequency of occurrence of each of the possible chance outcomes. The terms ”good” and “fair” are used to describe the quality of the seismic records.

**Table 2. Actual frequencies**



| Seismic interpretation | Actual outcome (number of wells) | | | |
|---|---|---|---|---|
| | Dry hole | 200 000 barrels | 500 000 barrels | Total |
| good and structure closed | 9 | 15 | 6 | 30 |
| good and structure not closed | 15 | 3 | 2 | 20 |
| good and no structure | 13 | 1 | 1 | 50 |
| sum | 37 | 19 | 9 | 100 |
| | | | | |
| Fair and structure closed | 3 | 6 | 1 | 10 |
| Fair and structure not closed | 9 | 1 | 0 | 10 |
| Fair and no structure | 12 | 3 | 0 | 15 |
| sum | 24 | 10 | 1 | 35 |

Thus in 9 cases where seismic records were good, and showed closed structure, the result was a dry hole etc.

The reliabilities or conditional probabilities can be calculated:

$$P(\text{good record and closed structure}|\text{dry hole})=\frac{\#\text{ favourable}}{\#\text{ possible}}=\frac{9}{30}=0.3$$

$$P(\text{good record and not closed structure}|\text{200 000 barrels })=\frac{\#\text{ favourable}}{\#\text{ possible}}=\frac{3}{20}=0.15$$

All the conditional probabilities are calculated in the same manner and the results are shown in Table 3.

The actual outcome is represented by columns, and the seismic indication prior to drilling is represented by the rows. $P(\text{good record and closed structure}|\text{dry hole})$ is found in the first column in the first row.

**Table 3. Conditional probabilities**

| Seismic interpretation | Actual outcome | | |
|---|---|---|---|
| | Dry hole | 200 000 barrels | 500 000 barrels |
| good and structure closed | 0,3 | 0,5 | 0,2 |
| good and structure not closed | 0,75 | 0,15 | 0,1 |
| good and no structure | 0,86 | 0,07 | 0,07 |
| Fair and structure closed | 0,3 | 0,6 | 0,1 |
| Fair and structure not closed | 0,9 | 0,1 | 0 |
| Fair and no structure | 0,8 | 0,2 | 0 |

The information gives us the total probabilities for both tool and interpretation accuracy, The author emphasizes that although probability assignments have been equated with past frequencies in his example, an operator does not have to do that.

Instead the decision maker or the geologist can interrogate his own experience, judgement or information in order to assign personal probabilities. The decision maker could also refer to past frequencies but modify them to a particular venture based on his or her experience, judgement or other information.

The method of assigning personal probabilities is described in the next section.

## Subjective assessment

It is recommended that reliability interviews with experts are conducted when we do not have a statistically relevant sample from previous trials. This is often the case in the oil and gas-industry because

1) We are unable to obtain a statistically significant number of trials.
2) We can only gather indirect information.
3) We can only obtain information in a sample of the entire population we are trying to describe.

The reliability of an expert's interpretation of a possible state of nature is dependent on both tool accuracy and interpreter accuracy. These in turn may be affected by interpreter bias, the true state of nature, the environment in which the information is to be gathered and the correlation in between the information sample and the population to be characterized.

Figure 8 is based on Coopersmith et al. (2006) and illustrates these dependencies:

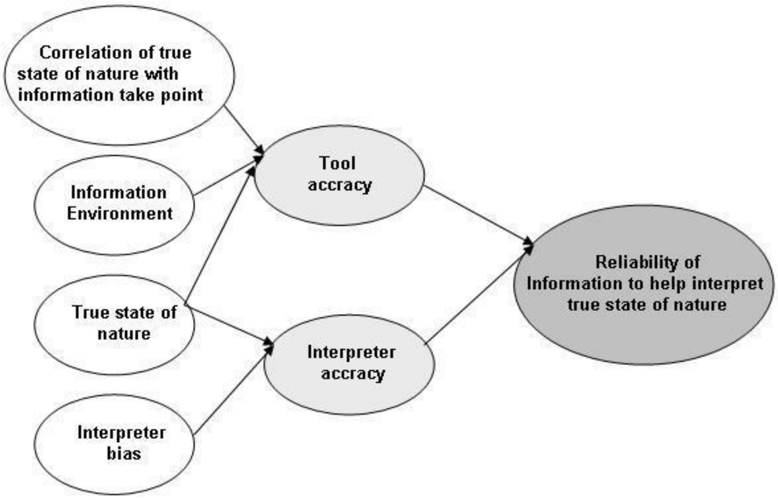


**Figure 8. Tool- and interpreter accuracy**

In Coopersmith et al. (2006) there is a list of 9 questions or steps in conducting the interview. The purpose is to counteract biases and consider relevant objective data and other factors.

These 9 steps are incorporated in the development-process of the reliability-assessment model in chapter 6.

The steps are:

1) Describe the uncertain variable to be measured.
2) Describe the information being considered.
3) Describe the factors which are relevant to the information being reliable in helping correctly predict the variable being measured.
4) Could the environment the information is collected from, affect the accuracy of the information?
5) Might the information be more accurate at helping interpret certain states of nature?
6) How representative is the sample-size of the variable being measured?
7) Describe possible outcomes of the information and what they would imply about the measured variable
8) If the true state of nature is Y, what would you expect the information to display?
9) Determine the reliability to correctly interpret the true state of nature, and the chance that the state of nature may be misinterpreted.

## Numerical assessment

In the article by Bickel et al. (2006) the authors link seismic accuracy-assessment to observable seismic data. The authors of this article are concerned about valuing seismic information.

Bayes’ Theorem is used for probability updating in VoI calculation, but here the authors have a slightly different approach.

They assume that reservoir properties and seismic signals are jointly normal distributed. The benefit of this assumption is that the posterior distribution also is normally distributed and there are simple analytic expressions for both the expectation value and variance of the posteriors.

In other words they do not go the way through reliabilities and Bayes Theorem. They calculate the posterior distribution directly.

Some inputs variables are needed for these formulas and they are based on relationships between seismic measurement and reservoir properties.

The authors include the reservoir-properties porosity, water saturation and reservoir thickness. They first define an empirical model that relates seismic compressional- and shear wave-velocities to porosity. Then they introduce a model relating density to porosity.

In both these models they take advantage of mathematical perturbation theory to account for the non-uniqueness in rock property distributions associated with variations in rock composition.

These methods are used to find an approximate solution to a problem which cannot be solved exactly. This is done by starting from the exact solution of a related problem. Perturbation theory is applicable if the problem at hand can be formulated by adding a "small" term, $\varepsilon$, to the mathematical description of the exactly solvable problem. The $\varepsilon$ terms are here selected from the Normal distribution. So instead of giving an exact value for each parameter $A = A_0$, the parameter is represented by a geometrical series.

$$A = A_0 + \varepsilon \cdot A_1 + \varepsilon^2 \cdot A_2 + ..... \qquad (6)$$

They also include water-saturation by introduce Gaussmann-equations well-known in geophysical-theory.

To come around the problem of tuning[1], the seismic measurement is the conventional reflection coefficient rather than the seismic amplitude. In this calculation one need the reservoir thickness. To count for uncertainty, the thickness is also given by a geometrical series instead of one single number.

The noise or error in seismic data acquiring is also incorporated. This is done by referring to studies done on acquisition-techniques where mean errors and standard-deviations are calculated. The authors therefore include random errors and standard-deviations corresponding to these levels. These static errors refer to both elevation changes and estimated near-surface velocities.

To introduce spatial correlation the authors use Fourier analysis or filtering. They assume that this kind of processing does not introduce significant error.

The relation-ships needed in the formula for expected posterior can now be generated using Monte-Carlo simulations and put into the expressions for expectation-value and variance.

---

[1] A phenomenon of constructive or destructive interference of waves from closely spaced events or reflections. Schlumberger Inc. (2007). Oilfield Glossary.

# 6. Reliability-assessment model

Inspired by the 9 steps to counteract biases and consider relevant objective data in conducting a reliability interview, a reliability-assessment method is developed. The aim is to make a procedure to follow to make reliability assessment in the best possible way. What is meant by the best possible way is discussed on page 11.

Like Bickel et al. (2006), the model developed in this chapter, link reliability to measured quantities.

The approach described in this chapter is useful in relation to all information-sources, but because it requires an understanding of the information source and the theory behind it, I will focus on one information source when developing the model. 3D seismic is chosen as information-source.

The role and requirement of 3D seismic is different in each stage of the hydrocarbon cycle. This is shown in Table 4 from Ritchie (1986)

**Table 4. Seismic requirements in the hydrocarbon circle**

| Phase | Need | Objective |
|---|---|---|
| **Exploration** | Delineation | Reserve estimates and well placements |
| **Development** | Descripton | Reservori management and life extention |
| **Production** | Simulation | Process selesction |

As we progress from the exploration to development phase, the requirements from the information proceed from macro-level of delineation of reservoir-boundaries to the micro-level of the pore-space.

At each stage, increasing detail is required as a comprehensive description of the reservoir is developed incorporating all available data-sources.

When developing the reliability-assessment model, the focus will be on the exploration-phase. In this phase we often lack enough data to do simulations and because this model does not use simulations it is applicable.

### 6.1 Reliabilities to be assessed

I will use the conceptual way to describe the VoI introduced by Head (1999).

| | |
|---|---|
| $P_s$= P(scientific success) | Probability of Scientific Success |
| $P_{mefs}$=P(minimum economic field size) | Probability of Minimum Economic Filed Size |
| $P_{es}$=P(economic success) | Probability of Economic Success |
| $P_{ef}$=P(economic failure) | Probability of Economic Failure |
| EMV | Expected Monetary Value |
| NPV | Net Present Value |

The probability of scientific success is defined, by Head (1999), as the probability of encountering a working hydrocarbon system capable of delivering measurable hydrocarbons to surface.

P(economic success) is the probability of finding a working reservoir large enough to exploit commercially.

$$P_{es} = P_s \cdot P_{mefs} \tag{7}$$

The probability of minimum economic filed size is determined by discovery-and operating costs, existing infrastructure, local tax and royalty systems and maturity of the basin.

Although seismic has a cost, I will keep this out of the costs affecting $P_{mefs}$ and focus only on how seismic influence the probability of scientific success. Seismic accuracy is directly related to costs, but this will be discussed later in this chapter.

In more detail, the upper branch (with information) in decision-tree in figure 1, will look like the one in Figure 9 below. Here a schematic form is used to keep it simple.

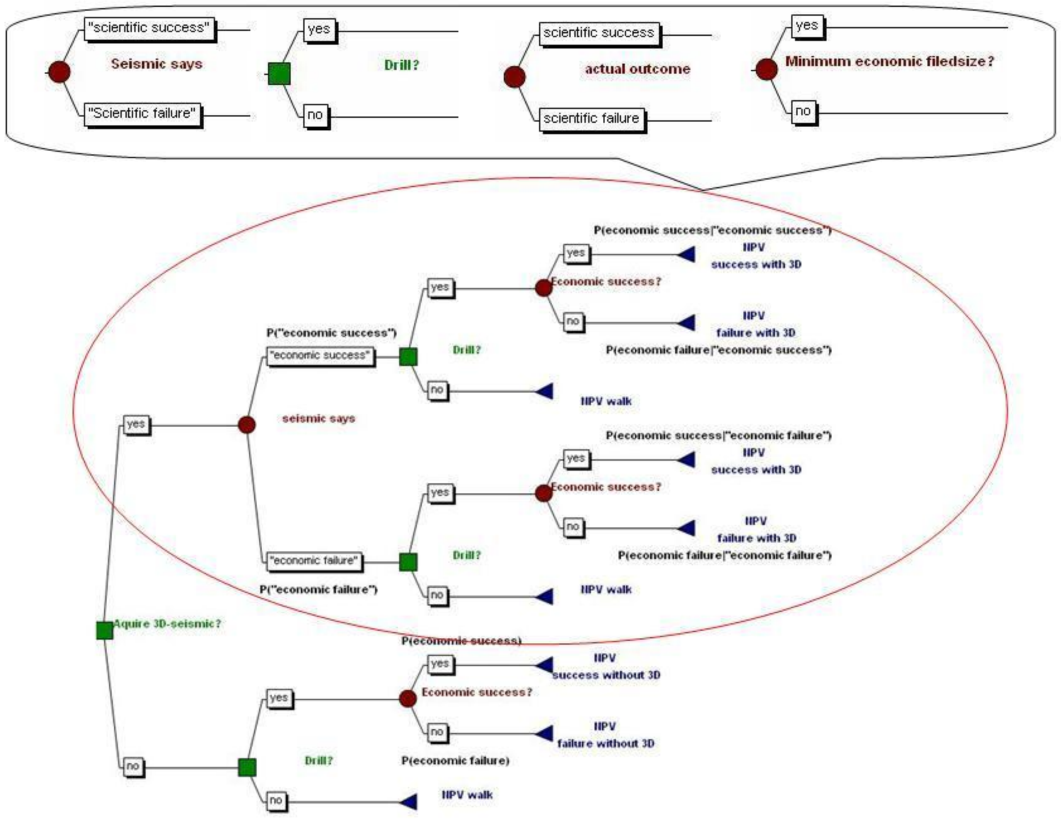


**Figure 9. Schematic decision-tree**

The formation of hydrocarbon reservoirs requires presence of the following geological features, partly based on Mussett and Khan (2000):

1) Source-rock: Often clay.

   Organic matter usually remains of plants and animals need to be buried in a source-rock that protects them from being destroyed by oxidation. Here the organic matter changes by bacterial action operating at high temperatures.

2) Migration:

   Hydrocarbon-droplets are squeezed out of the source rock because it is lighter than water. They tend to move up but also often sideways.

3) Seal/ Cap-rock: Often Shale

   Hydrocarbon is prevented from leaking to the surface by an impervious cap-rock.

4) Reservoir-rock: Often Sandstone or Carbonate

Hydrocarbon has to be in a porous and permeable reservoir-rock

5) Trap

For the hydrocarbon to be commercially useful, it has to be concentrated into a small volume. There are different types of traps:

a) Structural traps

Result from tectonic processes which produce folds, domes, faults and so on.

b) Stratigraphical traps

These are formed by litological variation at the time of deposition, such as lens of permeable and porous sandstone or carbonate-reef surrounded by impermeable rocks.

c) Combined traps

Both structural and straigraphical traps. Example of this is low density salt squeezed upwards to form a salt-dome. It causes hydrocarbon to concentrate upwards and also blocks their escape.

Figure 10 illustrates these geological features:

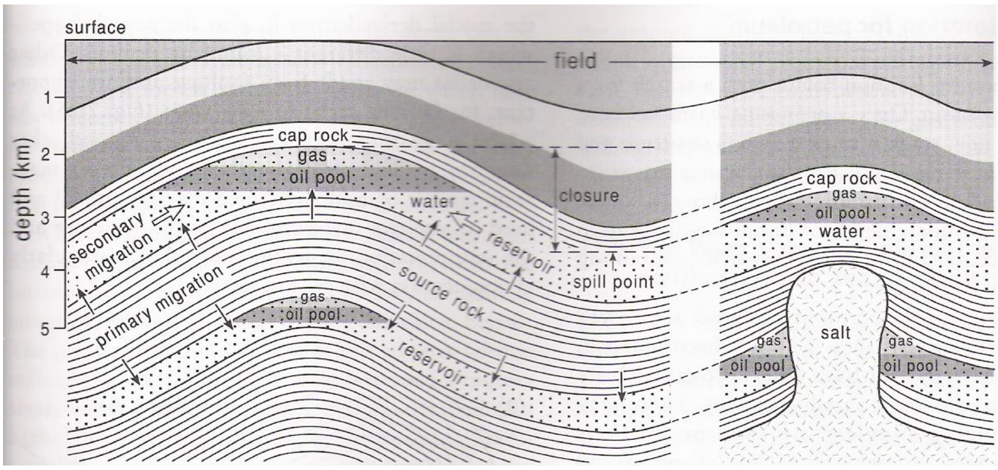


**Figure 10. Geological features From Mussett and Khan (2000)**

Scientific success can only occur if all these elements are working.

$$P_s = P(source \cap seal \cap migration \cap reservoir \cap trap) \qquad (8)$$

A commonly used assumption is that all the events are independent. If we adopt it we can write the probability for scientific success as

$$P_s = P_{source} \cdot P_{seal} \cdot P_{migration} \cdot P_{reservoir} \cdot P_{trap} \qquad (9)$$

This means that going into further detail in the decision-tree, it would look like the one in figure 11.

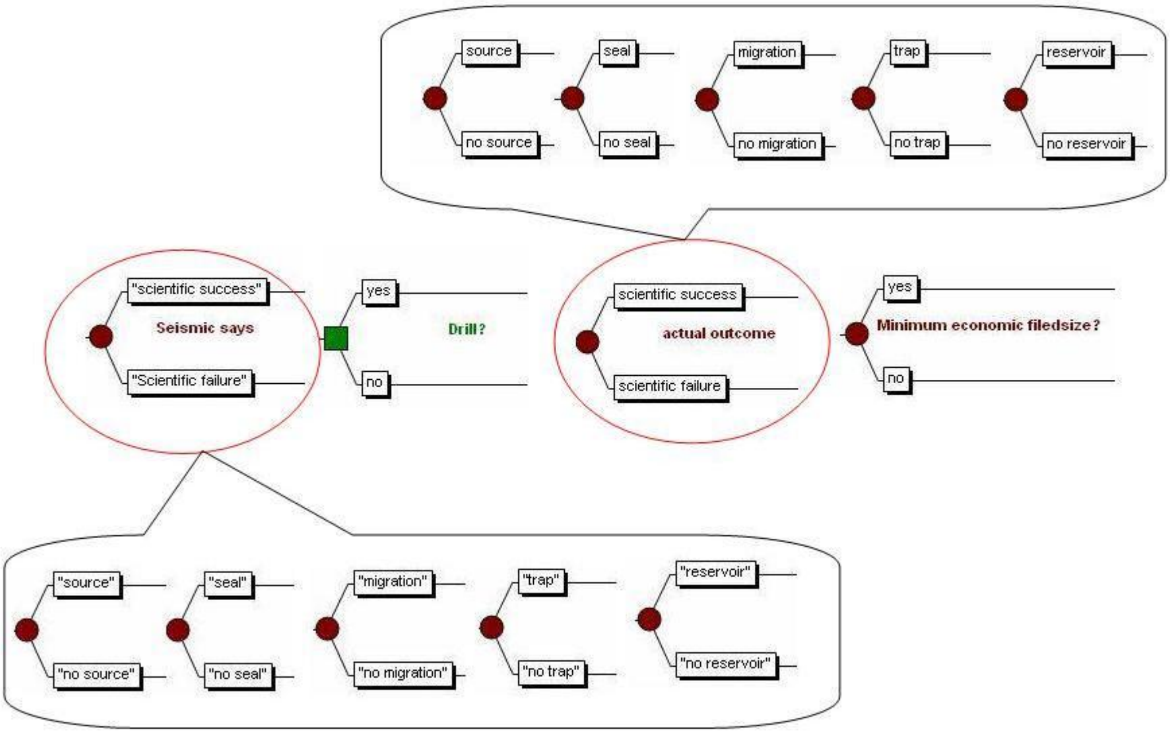


**Figure 11. Decision-tree in more detail**

Scientific success is the outcome when following only the upper branches.
Scientific failure is all the other combinations. Because $P_{ef} = 1 - P_s$ we need only to calculate $P_s$.

The probability for source, seal migration etc. in figure 11, are the posteriors. Because the events are independent the posteriors

$$P(source \mid "source" \cap "seal" \cap "migration" \cap "trap" \cap "reservoir") = P(source \mid "source") \quad (10)$$

It is similar for the other events.

The reliabilities needed for calculating these posteriors are therefore

$P(\text{"}source\text{"} \mid source)$

$P(\text{"}seal\text{"} \mid seal)$

$P(\text{"}migration\text{"} \mid migration)$

$P(\text{"}trap\text{"} \mid trap)$

$P(\text{"}reservoir\text{"} \mid reservoir)$

The method I will develop for assessing these reliabilities is based on the link between the five geological features (seal, source, trap, migration and reservoir) and observable properties of the prospect[2] on hand.

To make these connections it is important to understand the theory behind the seismic and what the seismic is expected to tell us.

---

[2] An area of exploration in which hydrocarbons have been predicted to exist in economic quantity. A prospect is commonly an anomaly, such as a geologic structure or a seismic amplitude anomaly that is recommended by explorationists for drilling a well. Schlumberger Inc. Oilfield Glossary.

## *6.2 Geophysics*

In this section I will explain the theory behind reflection seismology needed to indicate dependencies between prospect properties and the acquired data. To do this it is useful to first introduce some basic theory on wave-theory and geophysics.

This section is based on the parts of the book by Mussett and Khan (2000) that are most useful for this purpose.

Hydrocarbon exploration begins with a search for a sedimentary basin.[3] Once a basin has been found, its depth can be measured by seismic reflection and refraction surveys.

The next stage is to examine its structure for features necessary for commercial extractable hydrocarbons. This is a source rock, adequate depth and reservoir rocks containing traps below a cap-rock.

### Seismic waves

If we can se the waves travelling, it is easy to measure how fast they are moving by using the formula

$$v = f \cdot \lambda \qquad (11)$$

Where v is the wave-speed, f is the frequency. That is the numbers of complete vibrations in a unit of time and $\lambda$ is the wavelength, the repeat length often measured between successive crests or compressions.

But we can not see the waves moving inside the earth and we therefore need a way of “marking” waves so that their progress can be observed. A way of doing this is to generate just a few waves and time how long it takes before the ground some distance away begins to move. A very short series of waves is called a pulse

---

[3] Any geographical feature exhibiting subsidence and consequent infilling by sedimentation. Wikipedia, t. f. e. (2007) Reflection seismology

Waves propagate outward from their source in all directions. In seismology we are interested only in what happens in one direction, and we only need to consider one part of the wave-front. The path of only a thin portion of the wave-front, or pulse, forms a ray.

## Reflection and refraction

When waves strikes a interface separating two materials they are in general partly reflected and partly refracted (transmitted) into the second material. This is illustrated in Figure 12.

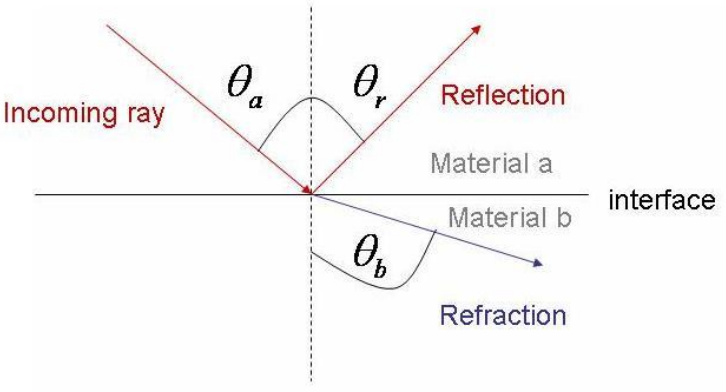


**Figure 12. Reflection and refraction**

Based on Freedman and Young (2000)

The law of reflection says $\theta_a = \theta_r$ (12)

The law of refraction, Snell's law, says

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a} = \frac{c/v_b}{c/v_a} = \frac{v_a}{v_b} \tag{13}$$

Here $\theta_a < \theta_b$, so that $v_a < v_b$

Where c is the speed of light, and $v_a$ and $v_b$ are the wave-speed in material a and b. Generally $v_a$ and $v_b$ are different in different materials, because the angles $\theta_a$ and $\theta_b$ are usually different. Because the frequency does not change, the wave-length λ is general different in different materials. See eq. (11)

## Reflection seismology

Now we have the background-knowledge needed to understand the theory of reflection seismology.

In this section I will go relatively deep into detail when deriving the equations. This is because the reliability assessment model builds upon dependencies between different variables, and these formulas represent some of the dependencies.

Reflection seismology, or seismic, is used to map the subsurface structure of rock formations. Seismic technology is used by geologists and geophysicists who interpret the data to map structural traps that could potentially contain hydrocarbons.

The general principle is to send sound energy waves into the earth, where the different layers within the earth's crust reflect back the energy. The reflected energy waves are recorded over a predetermined time period. The reflected signals can then be processed using specialist software which will result in processed seismic profiles. These profiles or data sets can then be interpreted for possible hydrocarbon reserves.

It is most easily explained by describing a simple example.

A ship sails along emitting pulses of seismic energy, which travel downwards, to be partially reflected back up from the sea floor and from interfaces in the rocks called reflectors.
When a pulse reaches the surface it is detected by seismic receivers.

At the same time a pulse is emitted a pen begins to move across a roll of paper. It is connected to the receiver so that every reflected pulse produces a wiggle on the trace. After a short interval the ship has moved along, the process repeats and the paper is moving slowly along and each trace are slightly to one side of the previous one. The wiggles on the separate traces lines up to show the interfaces.
This is illustrated in Figure 13 from Mussett and Kahn (2000)

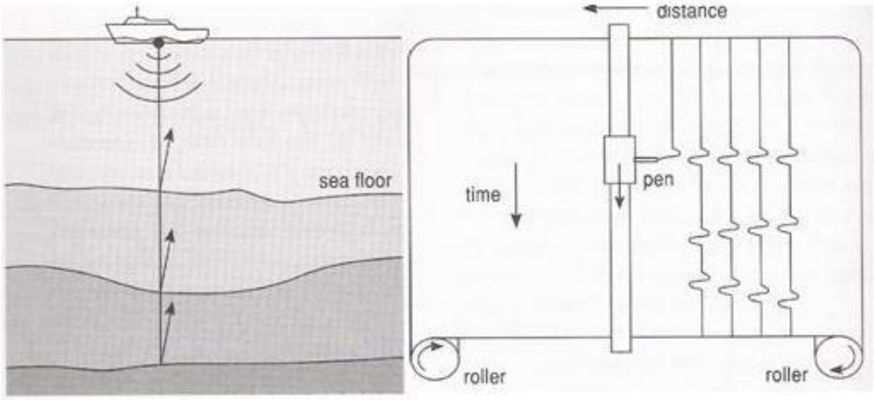


**Figure 13. Reflection seismology**

The out data may look like on the left side of fFigure 14 from Mussett and Kahn (2000).

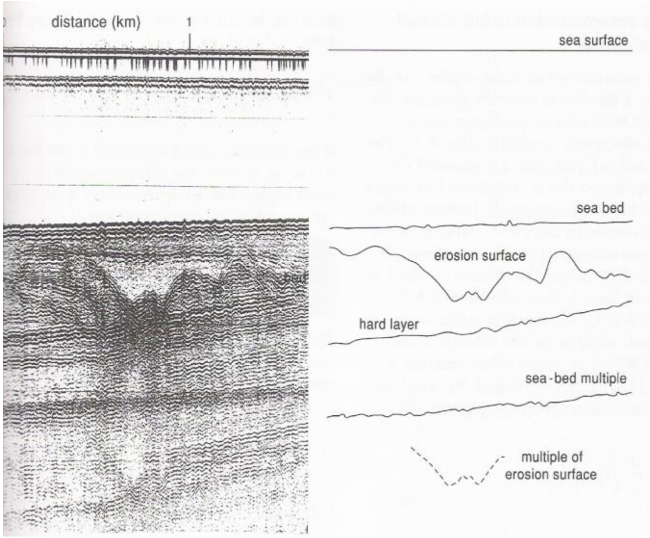


**Figure 14. Seismic image**

Reflection seismic is an inverse problem. That is, given a set of data collected by experimentation and the physical laws that apply to the experiment, one wishes to develop an abstract model of the system being studied. The results obtained are usually not unique, and may be sensitive to relatively small errors in collecting, processing or analysis.

As the figure above shows, the result can give a very direct picture of the subsurface structure, but it is not a true vertical section for several reasons.

1) The vertical scale is time. Since velocity varies with depth, times can not be easily converted into depth as they can for measuring water depths.

To find the velocities, and hence the depth, we need a number of receivers along the line.

The shortest reflected ray path is the vertical one, the rays that reach receivers to either side, travel a longer distance, taking extra time, Δt. This is shown in the t-x diagram in Figure 15 from Mussett and Khan (2000)

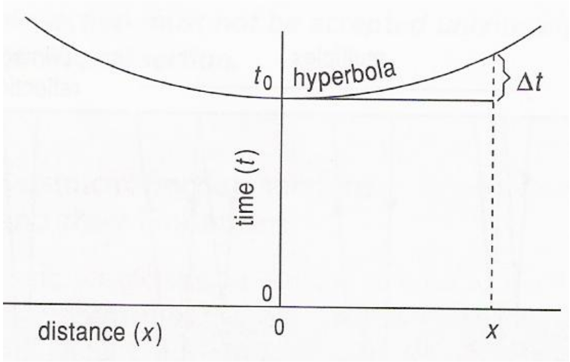


**Figure 15. t-x diagram**

In figure 16 a pulse is emitted in point S. A receiver, $R_0$, is also placed in this point. The next receiver, $R_1$, is placed in a distance d from the emitting-point. There are two layers each with different associated velocity $v_1$ and $v_2$. The thickness of the uppermost is $h_1$.

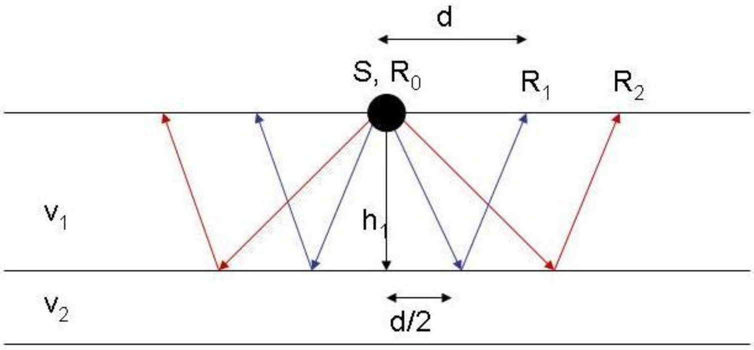


**Figure 16. Normal move-out**

The time it takes for the ray to reach receiver $R_0$, is found by using the basic formula from mechanics

$$x = v \cdot t \tag{14}$$

Where x is the distance, v is the velocity and t is the time.

With the quantities from figure 17 it is

$$2h_1 = v_1 \cdot t_0$$

Solved with respect to $t_0$ give

$$t_0 = \frac{2h_1}{v_1} .$$

To find the time it takes to reach receiver $R_1$, one have to use Pythagoras theorem to find the distance the blue ray is travelling. This is two times the hypotenuse.

$$x = 2\sqrt{(\frac{d}{2})^2 + (h_1)^2}$$

Put into the formula and solved with respect to $t_1$, give

$$t_1 = \frac{2}{v_1}\sqrt{(\frac{d}{2})^2 + (h_1)^2}$$

To get an expression for the extra time it takes for the ray to follow the blue line, rather than the vertical one:

$$t_1^{\,2} = (t_0 + \Delta t)^2 = [\frac{2}{v_1}\sqrt{(\frac{d}{2})^2 + (h_1)^2}\,]^2$$

$$t_1^2 = t_0^2 + 2t_0\Delta t + \Delta t^2 = (\frac{d}{v_1})^2 + \frac{2^2 h_1^2}{v_1^2} = (\frac{d}{v_1})^2 + t_0^2$$

$$2t_0\Delta t + \Delta t^2 = (\frac{d}{v_1})^2$$

$$\Delta t + \Delta t^2 = \frac{d^2}{2t_0 v_1^2} \tag{15}$$

When the offsets, d, are small compared to thickness of the layer, so that the rays are never more than a small angle away from the vertical, $\Delta t + \Delta t^2 \approx \Delta t$ , so that

$$\Delta t = t_1 - t_0 \approx \frac{d^2}{2v_1^2 t_0} \tag{16}$$

This gives us the seismic velocity for the topmost layer.

$$v_1 \approx \frac{d}{\sqrt{2t_0\Delta t}} \tag{17}$$

d, $t_0$ and Δt are measured from the t-x diagram.

For deeper layers, we use a slightly different formula because of the refractions.

$$v_{rms} = \sqrt{\frac{v_1{}^2\tau_1 + v_2{}^2\tau_2 + ....v_i{}^2\tau_i}{\tau_1 + \tau_2 + ...... + \tau_i}} \tag{18}$$

Where $\tau_i$ is the one way time in layer i.

The velocity of any particular layer can be calculated using information for just the reflectors the layer lies between:

$$v_{layer} = \sqrt{\frac{v_{rms,\text{Base reflector}} \cdot t_{\text{Base reflector}} - v_{rms,\text{Top reflector}} \cdot t_{\text{Top reflector}}}{t_{\text{Base reflector}} - t_{\text{Top reflector}}}} \tag{19}$$

The thickness of each layer is now easy to find using $x = v \cdot t$

$$h_{layer} = v_{layer}\left(\frac{t_{\text{Base reflector}} - t_{\text{Top reflector}}}{2}\right) \tag{20}$$

The other reasons why the seismic image is not a true vertical section are:

2) Reflections may not come directly from below the source since they reflect at right angles to the interface.

   If a reflector is dipping, both its apparent position and dip on a seismic section are changed.

   If the reflector is curved, there will be more than one path between the source (shoot point) and the receiver, and the distortions may be complex.
   Correcting for displacement of the position and shape of a reflector that is not horizontal is called migration. Because it is complicated and uses a lot of computer-time it is sometimes not carried out.

3) There may be multiple reflections in addition to the primary reflections.
   This is associated with the strongest reflectors. Figure 17 illustrates a multiple reflection

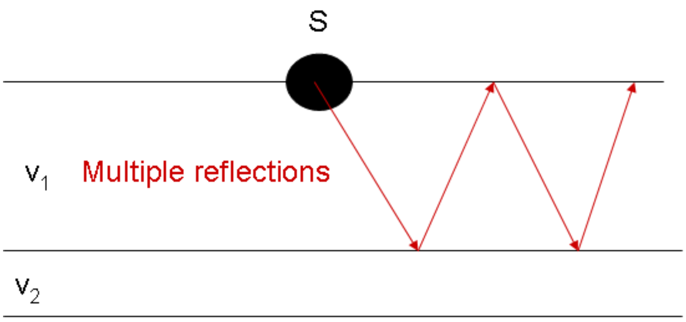


**Figure 17. Multiple reflections**

The reflection coefficient determines how strong a reflector is, based on the incoming and reflected amplitudes. The reflection coefficient is defined by Freedman and Young (2000) as

$$R = \frac{a_{reflected}}{a_{incident}} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \tag{21}$$

It is worth mention that a boundary between two lithologies needs not to be a detectable interface. A seismological interface need not to be a geological boundary, an example of this is oil-gas interface.

4) When the interfaces are not continuous, for instance it may have been offset by a fault, the waves are diffracted and it is hard to tell exactly where the fault is. Migration removes diffraction effects.

5) Often reflections are weak, particularly those from deep interfaces.
Noise is unwanted variations in the quantities being measured. The signal is the wanted part. The $\frac{\text{Signal}}{\text{Noise}}$ can be improved by Stacking. This is done by repeating the readings and taking their average. The noise is random and will cancel. Another method is signal processing, using Fourier-analysis or filtering.

6) Vertical resolution is not good enough
Vertical resolution is the last separation at which the interfaces can be distinguished. The resolution is poor when:

a) The interfaces are close together.
This is like shrinking the middle layer to nothing, resulting in a continuous medium which obviously can not produce reflections. In practice two pulses are difficult to distinguish when they are less then about half of a wavelength apart.

The resolution can be improved by shorter wavelength of the pulse, but these are more rapidly refracted and would not reach deeper reflectors.

b) The interface is a gradually change of velocities and densities extending over more than half a wavelength there may be no reflections.

The workflow from acquirement to implementation of 3D seismic is based on Mussett and Khan (2000).

1) Data acquisition, taking measurements.

2) Data reduction

3) Stacking/ signal processing

4) Modelling

This step involves modelling the reduced data in physical terms. A model is a body or structure described in terms of depth, size, density etc. that could account for the data being measured. Values calculated from the model are compared with the actual measures. The model is almost always simpler than reality for several reasons:

a) Trying to deduce form of a causative body from the signal is the inverse problem and often difficult because different shapes can give the same reflections.

b) Sometimes it is impossible to deduce the causative body directly from the results. Then one have to guess a model, calculate the values it would produce and compare with the observations in an iterative process. These models have to be simple.

c) Because of noise and errors of measurement, it may be difficult to find the exact shape and size of the anomaly (the part of a profile that is above or below the surrounding average)

d) The receivers may not be close enough to reveal all the details of the signal. We say that the resolution is not sufficient.

5) Geological interpretation

The physical model has to be translated into geological terms. One needs to take account to all available information available from the geological context in the area.

6) Displaying the results

In the end of the survey the results have to be presented in some form and this offers an opportunity to emphasis features. The human eye and brain together have very sophisticated abilities to pick up lines, curves, circles and so on. But the data need to be presented in a suitable form.

7) Data processing

It the features of interest are not obvious there are further strategies of processing that will enhance the features. This is mathematical strategies.

## 2D vs. 3D seismic

It is useful to understand the difference between 2D-and 3D seismic. When deciding to shoot 3D seismic or not, the current information is often based on 2D seismic.

In a 2D survey, there may be 1 km or more between each geologic line. (It is where the seismic is actually shot). The area under consideration consist therefore of a grid of geological lines with space between them. In the space between the lines the geologists have to use interpolation techniques to create an image of the underground.

In a 3D survey on the other hand the geological lines are close together. Often there are only 12.5 m or 25 m between the lines.
Because of this the area under consideration, consist of a volume, not only a grid. Every point underground is, in addition, more accurately determined because emitted energy form different boat positions is reflected by the same reflector point.

The difference between 2D and 3D seismic is shown in the figure 18.

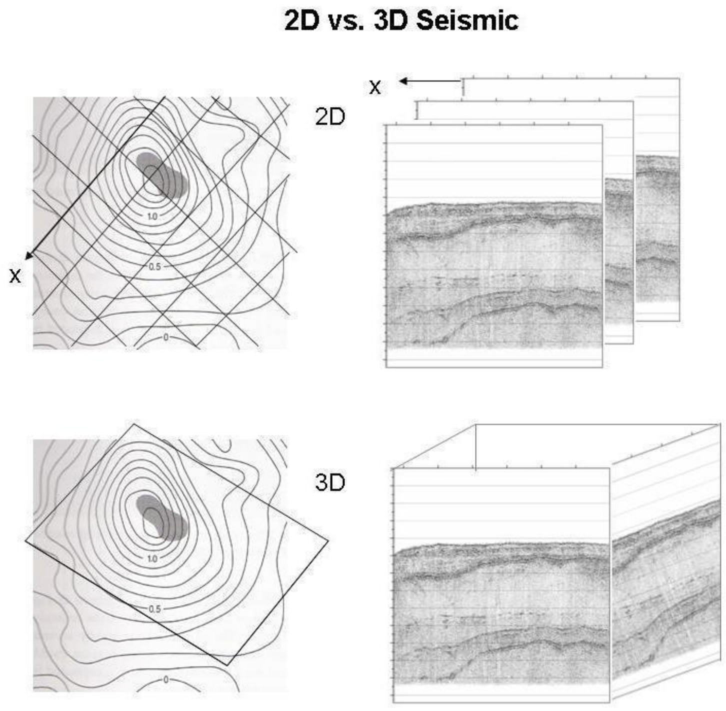


**Figure 18. 2D vs. 3D seismic**

## 6.3 Indicating dependencies

Based on geophysical knowledge we will now make a figure indicating dependencies between acquired data, modelled variables, geological features, prospect properties and reliability.

First I will summarize what the seismic is expected to tell us:

1) Structure: Downcasts, deep, relief and traps.
2) Stratigraphy: The layers and the thickness of them
3) Lithology: Type of rock.
4) Depth: Found by converting time-data using velocity information.
5) Fluid**:** Sometimes seismic can tell the presence of gas, oil, or water directly, DHI.

The reliability-assessment model to be developed in this section is based on the dependences:

1) Between the five geological features, described in section 6.1, needed for scientific success and the factors the seismic are supposed to tell us about.
2) Between the factors the seismic is expected to tell us and the acquired data (time and amplitude)
3) Between the acquired data and the factors influencing their accuracy.
4) Between the accuracy-influencing factors and the prospect properties that make them appear.

These dependencies will be referred to as dependencies 1 to 4 in the following and they are illustrated in figure 19. The figure is based on information from previous sections.

The factors influencing the accuracy of the acquired data and the prospect properties making these factors appear, are discussed in chapter 6.2 pages 45-50.

The relation between the acquired data, amplitude and time, and the modelled data velocity and density are described by the equations in chapter 6.2.

What the seismic is expected to tell us is discussed in chapter 6.3.
Depth and stratigraphy are functions of velocity. See equation (19) and (20).

Lithology can be determined using the density of the rocks and the wave-speed. See both equation (13) and the comment associated with it, and equation (21).

The geological features required for a well-working reservoir are explained in chapter 6.1 pages 38-39.

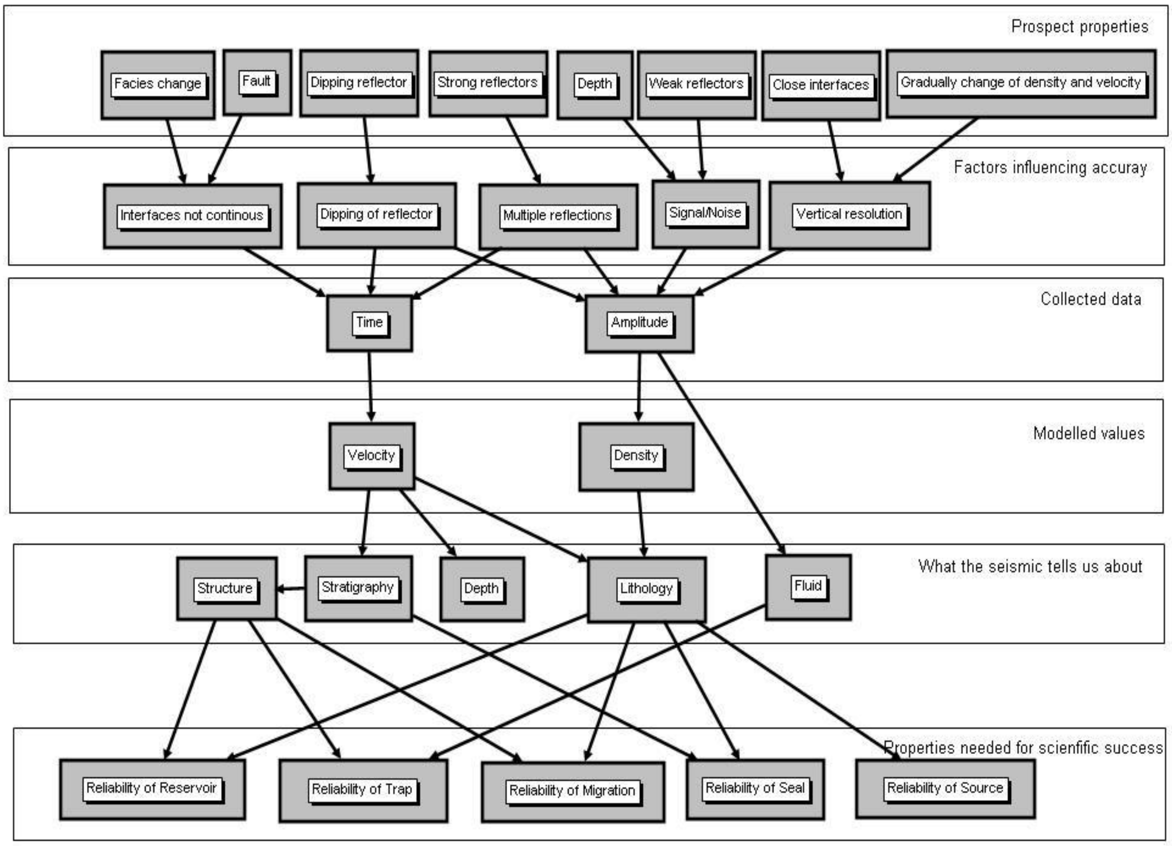


Figure 19. Dependencies

The central point in this model is to express the probability of the appearance of each of the geological features needed for scientific success, in terms of collected data.

Based on figure 19 we can express dependences 1-4 in the following ways:

**Dependencies 1**

$$\begin{aligned}
&P(\text{source-rock}) && \leftarrow F_1(\text{Lithology, Amplitude})\\
&P(\text{migration}) && \leftarrow F_2(\text{Depth, Lithology, Structure})\\
&P(\text{seal}) && \leftarrow F_3(\text{Lithology, Stratigrapy, Structure})\\
&P(\text{reservoir}) && \leftarrow F_4(\text{Structure, Lithology})\\
&P(\text{trap}) && \leftarrow F_5(\text{Lithology, Structure, Fluid})
\end{aligned}\tag{22}$$

Where $F_1$,$F_2$, $F_3$,$F_4$ and $F_5$ are unknown functions.

It is important to point out that there exists no such thing as a one-to-one predefined function indication source rock, migration and so on. This is the reason why there is no equal sign in the expressions above, but arrows to indicate dependencies.

**Dependencies 2**

These dependencies can be expressed by the modelled variables velocity v, and density ρ which in turn are functions of the acquired data amplitude and time.

$$\begin{aligned}
&\text{Lithology} && \leftarrow f_1(v, \rho) \leftarrow f_2(t, a)\\
&\text{Stratigraphy} && \leftarrow f_3(v, \rho) \leftarrow f_4(t, a)\\
&\text{Structure} && \leftarrow f_5\,(\text{Stratigraphy}) \leftarrow f_6(t, a)\\
&\text{Depth} && \leftarrow f_7(v) \leftarrow f_8(t)\\
&\text{Fluid (DHI[4])} && \leftarrow f_9(a)
\end{aligned}\tag{23}$$

Where $f_1$,$f_2$, …..$f_9$ are unknown functions.

We now assume that the main sources that make the seismic image differ from the true underground are the factors influencing accuracy in the collected data.

The probability for us to detect a source-rock on our seismic-image if there is really one underground is then expressed as

$$P(\text{“Source”} \mid \text{Source}) \quad \leftarrow g_1\,(\text{Accuracy in } t \text{ , Accuracy in } a)$$

This is the reliability. All the reliabilities can be expressed in a similar way:

$$\begin{aligned}
&P(\text{“Migration”} \mid \text{Migration}) && \leftarrow g_2\,(\text{Accuracy in } t \text{ , Accuracy in } a)\\
&P(\text{“Seal”} \mid \text{Seal}) && \leftarrow g_3\,(\text{Accuracy in } t \text{ , Accuracy in } a)
\end{aligned}\tag{24}$$

---

[4] Direct Hydrocarbon Indicator

P(“Reservoir” | Reservoir) ← $g_4$ (Accuracy in t , Accuracy in a)
P(“Trap” |Trap) ←g5 (Accuracy in t , Accuracy in a) This is the reliability.

Where $g_1$,$g_2$, …..$g_5$ are unknown functions.

**Dependencies 3**

Accuracy time ← $h_1$ (Interfaces not continuous, Dipping reflectors, Multiple reflectors) (25)
Accuracy amplitude ← $h_2$ ($\frac{Signal}{Noise}$, Vertical resolution)

Where $h_1$ and $h_2$ are unknown functions.

**Dependencies 4**

Interfaces not continuous ← $k_1$( Fault, Facies change)
Dipping reflectors ← $k_2$( Degree of dipping)
Multiple reflectors ← $k_3$( Strength of reflector (R) ) (26)
$\frac{Signal}{Noise}$ ← $k_4$ (Depth, Weak reflectors (R))
Vertical resolution ← $k_5$ (Gradually change of v and $\rho$, Close interfaces)

Where $k_1$,$k_2$, …..$k_5$ are unknown functions.

If all the functions above where well-defined, we could simply substitute the dependencies 4 into 3, 3 into 2 etc. Knowing the degree of presence of the arguments in the last functions ($k_1$,$k_2$, …..$k_5$), the reliability would be determined.

We assume that the accuracy decrease as the arguments get more dominant.
Based on the existing information about the prospect these properties are to an extent known prior to the 3D seismic survey. And hence, based on how striking each of them is expected to be, we can calculate the reliability of 3D seismic in this case.

If based on our previous information we assume that the prospect has many properties present that makes it hard for the seismic to give a correct image of the underground, we will expect the reliability to be less than if these properties were absent.

## *6.4 Assessing weights*

Functions like the ones above often do not exist, and even if they did, they would be unknown. Therefore we introduce weights to indicate how much each of the factors fault, facies change, dipping, strength of reflector (R) ,depth, weak reflectors, gradually change of v,ρ and interfaces close affect each of the reliabilities.

The dependencies are assumed to be linear, and the weights in each case have to sum to 1.

We can now write the dependencies as follows:

**Dependencies 1**

The individual weights indicate how important each of the elements is in determining the existence of each of the geological features.

| | | | |
|---|---|---|---|
| Source-rock | ← $w_1$ Lithology, $w_2$ Amplitude | $w_1+ w_2=1$ | |
| Migration | ← $w_3$ Depth, $w_4$ Lithology, $w_5$ Structure | $w_3+ w_4+w_5=1$ | |
| Seal | ← $w_6$ Lithology, $w_7$ Stratigrapy, $w_8$ Structure | $w_6+ w_7+w_8=1$ | (27) |
| Reservoir | ← $w_9$ Structure, $w_{10}$ Lithology | $w_9+ w_{10}=1$ | |
| Trap | ← $w_{11}$ Lithology, $w_{12}$ Structure, $w_{13}$ Fluid | $w_{11}+ w_{12}+w_{13}=1$ | |

**Dependencies 2**

| | | | |
|---|---|---|---|
| Lithology | ←$w_{14}$ t, $w_{15}$ a | $w_{14}+ w_{15}=1$ | |
| Stratigraphy | ←$w_{16}$ t, $w_{17}$ a | $w_{16}+ w_{17}=1$ | |
| Structure | ←$w_{18}$ t, $w_{19}$ a | $w_{18}+ w_{19}=1$ | (28) |
| Depth | ←$w_{20}$ t | $w_{20}=1$ | |
| Fluid | ←$w_{21}$a | $w_{21}=1$ | |

**Dependencies 3**

The individual weights express which of the factors that is most critical with respect to achieving a correct seismic image if they all have the same level of presence.

Accuracy time ← $w_{22}$ Interfaces not continuous, $w_{23}$ Dipping reflectors, $w_{24}$ Multiple reflectors $\quad w_{22}+ w_{23} +w_{24}=1 \quad$ (29)

Accuracy amplitude ← $w_{25}\dfrac{Signal}{Noise}$, $w_{26}$ Vertical resolution $\quad w_{25}+ w_{26} =1 \quad$ (30)

**Dependencies 4**

The individual weights express which of the factors that is most critical with respect to achieving a correct seismic image if they all have the same level of presence.

| | | | |
|---|---|---|---|
| Interfaces not continuous | ← $w_{27}$ Fault, $w_{28}$ Facies change | $w_{27}+ w_{28} =1$ | |
| Dipping reflectors | ← $w_{29}$ Dipping | $w_{29}=1$ | |
| Multiple reflectors | ← $w_{30}$ Strength of reflector (R) | $w_{30}=1$ | (31) |
| $\dfrac{Signal}{Noise}$ | ← $w_{31}$ Depth, $w_{32}$ Weak reflectors | $w_{31}+ w_{32} =1$ | |
| Vertical resolution | ← $w_{33}$ Gradually change of v and ρ, $w_{34}$ Interfaces close | $w_{33}+ w_{34} =1$ | |

All these weight have to be assessed by experts.

The total weight of each of the prospect-property on each of the geological properties can now be found by substitution the expressions in dependencies 4 into dependencies 3 etc.

The weights are multiplied together. To illustrate the substitution-process we here calculate the reliability P("Source" | Source). The approach is equivalent for the other geological features and the calculation is shown in the Excel spread-sheet in appendix B

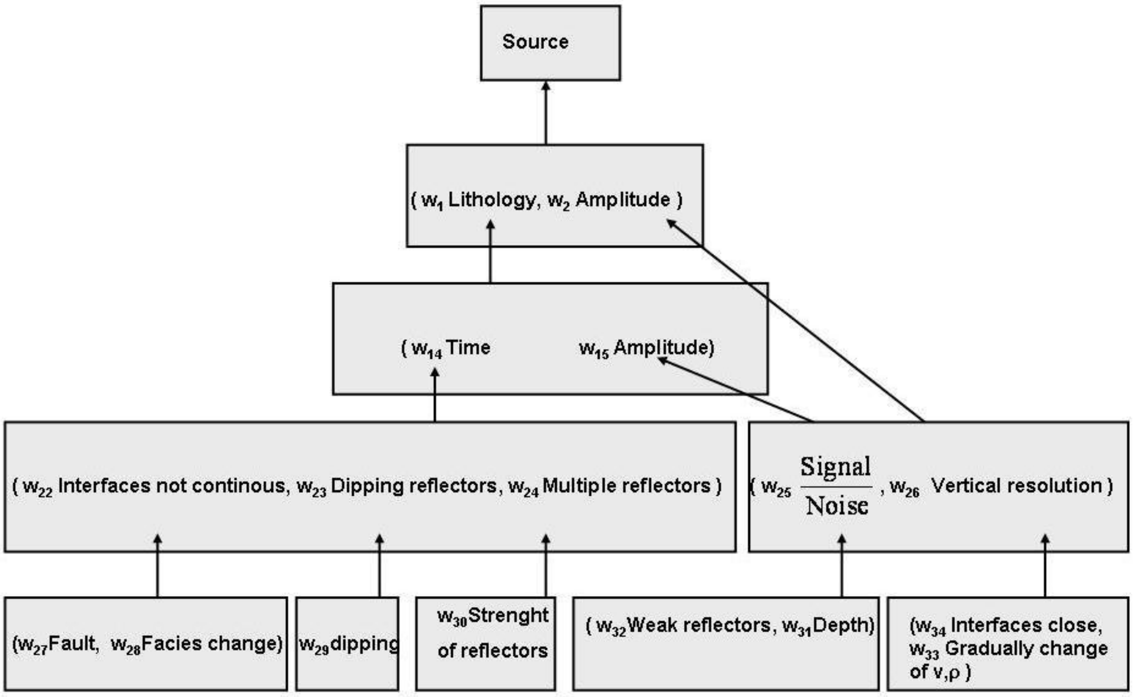


**Figure 20. Substitution in the real case**

Figure 20 illustrates how the substitution is done.
Starting from the bottom the arrows indicate which boxes that are substituted into which argument in the boxes above.

The properties affecting amplitude accuracy influence twice. Once in the amplitude with weight $w_2$ and once in the lithology related amplitude with weight $w_{15}$. The amplitude influences therefore totally with a weight $(w_1 \cdot w_{15} + w_2)$. The time influence totally $w_1 \cdot w_{14}$

Based on this observation we can draw figure 21. This illustrates the substitution-process used in the reliability-assessment model.

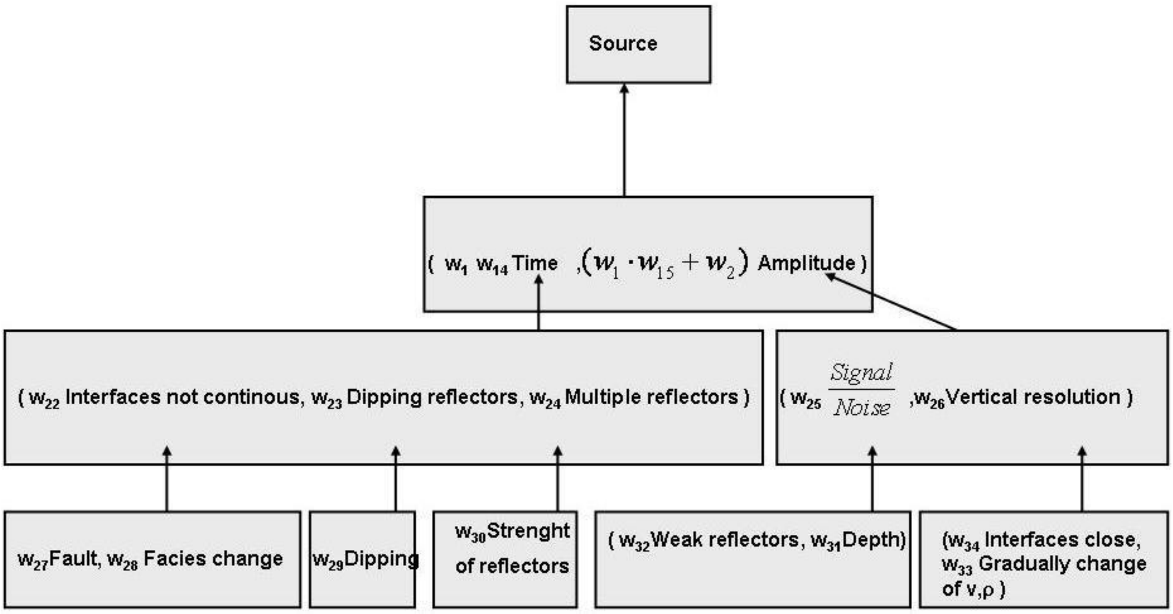


Figure 21. Substitution in the model

Based on the substitution process illustrated in figure 21, the total weight of each of the prospect-properties on the geological property source is calculated. The results are shown below.

| | | | |
|---|---|---|---|
| Fault | $w_{27} \cdot w_{22} \cdot w_{14} \cdot w_1$ | % | |
| Facies change | $w_{28} \cdot w_{22} \cdot w_{14} \cdot w_1$ | % | |
| Dipping | $w_{29} \cdot w_{23} \cdot w_{14} \cdot w_1$ | % | |
| Strength of reflectors | $w_{30} \cdot w_{24} \cdot w_{14} \cdot w_1$ | % | (32) |
| Weak reflectors | $w_{32} \cdot w_{25}(w_1 \cdot w_{15} + w_2)$ | % | |
| Depth | $w_{31} \cdot w_{25}(w_1 \cdot w_{15} + w_2)$ | % | |
| Interfaces close | $w_{34} \cdot w_{26}(w_1 \cdot w_{15} + w_2)$ | % | |
| Gradually change of v and ρ | $\underline{w_{33} \cdot w_{26}(w_1 \cdot w_{15} + w_2).}$ | % | |
| | $\sum = 100\%$ | | |

## 6.5 Prospect-properties

Now that this calculation is done, it is time to look at the prospect on hand. It is in this context we are going to find the VoI and hence the reliability. The reliability in this case is the conditional-probability that the seismic image show a source-rock if there is actually one presence, P("Source rock"|source rock).

If we, based on the information we have already got, assume that there are no faults in the area we are interested in, then we know that faults will not affect the seismic in a negative way. The seismic is in other words at least ( $w_{27} \cdot w_{22} \cdot w_{14} \cdot w_1$ ) % reliable. See the first expression in eq. (32)

If none of the properties are presence the reliability is 100%. If on the other hand all the properties are present at a maximum, they would ruin our ability to get an accurate image of the ground. The reliability would then be 0%.

For the numbers in between, let us say 0.3, we know that the total weight minus 30 % of the total weight is the contribution to the reliability from this property.
That is the reliability is at least $(w_{27} \cdot w_{22} \cdot w_{14} \cdot w_1) - 0.3(w_{27} \cdot w_{22} \cdot w_{14} \cdot w_1)$ %
Summing up all the properties, we get the reliability of source rock .

## 6.6 Implementation

In the appendix there is a print from an excel spreadsheet based on this model.
Both the calculations and the formulas are enclosed.

The grey cells are for user-input.

In the in-data part, the user puts in

1) The prior probabilities for seal, source, migration, reservoir and trap.
2) The expected presence of the prospect-properties fault, facies changes, dipping, strength of reflectors (R), depth, weak reflectors, gradually change of v and ρ, and close interfaces.

   This is gradually ranging form 0 to 1.

These assumptions are made based on the information already on hand. This is done every time the user wants to calculate the reliability of 3D seismic associated with a prospect.

The next parts of the spreadsheet just have to be implemented once. (But they may be revised later based on experience)

In the Dependencies 2 part the user puts in

1) The weights relating the modelled variables velocity and density to the "what the seismic are supposed to tell us about" properties.
2) The weights relating velocity and density to time and amplitude.

   These weights are assessed by using expressions the expressions derived in section 6.2

The spreadsheet calculates the total weight of amplitude and time on each of the properties lithology, depth, stratigraphy, DHI and structure.

In the Dependencies 1 part the user puts in the weights $w_1$ to $w_{13}$.
Actually there is an opportunity to include more of the "what the seismic are supposed to tell us about"- factors than the 13 listed above.

The spreadsheet calculates the total weight from time and amplitude accuracy on each of the geological feature seal, fault, migration, trap and reservoir.

The results from the “Dependencies 2” part are used in this calculation and that is why this part of the spreadsheet is after that one.

In the Dependencies 3 and 4 part of the spread-sheet the user puts in

1) The weights w22 to w26
2) The weights w27 to w34

The spreadsheet calculate the total weight from the prospect-properties fault, facies changes, dipping, strength of reflectors (R), depth, weak reflectors, gradually change of v,ρ  and close interfaces on time and amplitude accuracy.

In the out-data part the user get both the reliability and the posterior related to each of the geological features. The out-data are in the yellow cells.

## *6.7 Assumptions*

The model developed is kept simple in an attempt to explain the concept as clearly as possible. It is therefore based on the following assumptions:

1) Interpretation accuracy is linked only to the reliability of the seismic data time and amplitude.

2) Ideally all properties influencing time- and amplitude accuracy should be listed because they sum to 100 %. But just the ones assumed to have the largest influence are included.

3) The reliability is assumed to be symmetrical.
   That is
   P("source"| source) =P("no source"| no source)
   P("source"| no source) =P("no source"| source)
   This is equivalent for the other geological properties.

4) The accuracy decreases continuously as the accuracy-influencing factors gets more dominant.

5) The focus is on information accuracy.
   Interpretation-accuracy is indirectly included as we ask which properties that will make the seismic image less correct and harder to interpret correctly.

6) The dependencies are assumed to be linear.

7) The weights should be assed by a geophysicist and a geologist together.

8) The model builds on a "base-case" with the implementing techniques migration and processing.

## *6.8 Benefits and constrains*

### Benefits

The reliability assessment-model let the experts express their knowledge through weights and the degree of presence of prospect-properties instead of probabilities. This is directly related to their professional and technical skill. Probability is not.

Splitting the reliabilities up in seal, source, migration, trap and reservoir and then treating them independent of each other is convenient. The experts then can focus on one geological feature at the time when assessing reliability, instead of focusing on a financial concept like scientific success.

When assessing weights they have to think through all steps of their work.

The model incorporates the 9 questions suggested by Coopersmith et al. (2006) to counteract biases and consider relevant objective data and other factors mentioned in section 5.2.

When assessing the degree of presence of the different prospect-properties the experts have to analyse the prospect on hand based on previous information. This kind of analysis is also needed to design the 3D survey.

It is intuitively easy to understand because it does not involve advanced mathematics or simulations. The model links geological features to prospect properties and these are features well-known to the geologists.

It is easy to expand and the concept is useful in relation to other information-sources as well.

### Constrains

In addition to those resulting from the assumptions listed in chapter 6.6, there are other constrains. If the weights are poorly assessed, the reliabilities will be inaccurate. It is important to evaluate the weights now and then to se if they, based on experience, need to be updated.

## *6.9 Suggestions for further work*

It is possible to loosen up assumptions 1-3 in chapter 6.7. This is described in the following three sections.

### Include errors in the entire seismic processing chain.

Thore et al. (2001) describe the seismic workflow in greater detail and explain how each step of the seismic processing-chain has inherent uncertainty that can be evaluated.

Migration is one processing step with associated uncertainties. The goal in this step is to return reflectors to their true positions and collapse diffractions. This is crucial when dips are non-negligible.

The uncertainty depends on the accuracy of the velocity, and only in critical situation on the migration algorithm.

The authors present formulas for the displacement of a point P in x, y and z direction based on the velocity uncertainty which they determine using a statistical approach.

To include this in the reliability-assessment model it will be convenient to “translate” the uncertainty to percent and subtract it from the reliability. This can be done by dividing the uncertainty in vertical position by the depth of the point P.

Similar attempts can be done in relation to the other processing-steps.

Expressions for uncertainty can be found in geophysical literature as the article mentioned above. General expressions for errors in the numerical algorithms used can be found in mathematical literature. But these errors are often considered small relative to the uncertainty in the interpretation.

## Identifying more accuracy-influencing prospect properties

This means identifying more prospect properties and assess how they are related to the factors influencing accuracy.  In figure 19 this is the elements in the two upper boxes.

This work has to be done by experts. There may be special properties in the actual prospect environment influencing the time and amplitude accuracy. An example is ground roll described in Binbrek (1994)

## Non-symmetrical reliability

Non-symmetrical reliability is the case if
P(“source”| source) ≠ P(“no source”| no source) or
P(“source”| no source) ≠ P(“no source”| source)
This is the case in for example Begg et al. (2002).

This asymmetric appears if the seismic is more reliable when telling the absence than the presence of a geologic feature, or the other way around.

When some prospect-properties make the seismic picture less reliable, is it harder to recognize seal-rock, source, etc. if they are present, than conclude with the absence if that is the truth? If the answer is “yes” we have to make one model for the

$P("source"|source)$

$P("seal"|seal)$

$P("migration"|migration)$

$P("trap"|trap)$

$P("reservoir"|reservoir)$

And one for the

$P("no\ "|no\ source)$

$P("no\ seal"|no\ seal)$

$P("no\ migration"|no\ migration)$

$P(\text{"}no\ trap\text{"} \mid no\ trap)$

$P(\text{"}no\ reservoir\text{"} \mid no\ reservoir)$

The two models use the same input-values, but the weights assessed by experts will differ.

In addition to loosening up the constraining assumptions in the model, it can be expanded in other ways as well. This is described below.

## Reliability vs. costs

There are numbers of ways to improve seismic data quality both in the acquisition-phase and in data-processing. This will increase the costs and possibly result in project delay. This is also mentioned by Houck (2004) and Bickel et al. (2006)

To take this into consideration in the model, we can assume that the model is based on a “base-case” at a roughly predefined cost. If we include more processing techniques or improved acquisition-design we should count for that by adjusting the scale for prospect-property assessment. The maximum-value for some of the prospect properties would no longer be 1, but somewhat smaller.

If we for instance use a Dip move-out algorithm, DMO, to compensate for dipping reflectors, the maximum-value for dip would no longer be 1.
How much it should be reduced depends on how much of the negative effect from the dip-presence we can to remove. If we expect 10%, the max-value would be 0.9

It would be useful to make a list of additional processing techniques, their additional cost and how much of the negative effect from the prospect properties affecting reliability the technique can remove.

The work by Lansley (1999) includes many of the data-processing techniques used to interpret a correct structural image. A sensitivity analysis like the one in figure 7 would be useful when considering improvements in reliability like this.

If the technology improves, we can count for that by adjusting the weights in the model. Perhaps a dipping reflector is no longer a problem. Then the weight would be set to 0.

## More objective property-assessment

The prospect-property assessment can be made more objective by working out guidelines for how many degrees dip that corresponds to the values 0, 0.5 and 1.
This can be done in a similar manner for the other properties.

The challenge is here to decide which quantities that best describe the presence of the properties. This has to be done by the geologist to reflect the way he or she works.

An example is shown below:

Fault: Number per horizontal-meter
Facies change: Density per horizontal-meter
Dipping: Degrees
Strength of reflectors: Reflection-coefficient, R (Small values on R is good)
Weak reflectors: Reflection-coefficient, R (High values on R is good)
Depth: Meters
Interfaces close: Meters between interfaces/ wave-length
Gradually change of v and ρ: Velocity/ thickness of layer or density/thickness of layer

## Use of the model in relation to other information-sources

It is possible to use the concept of relating acquired data to observable accuracy-influencing properties in relation to other information-sources as well.

This requires that the decision-analyst understand what data are collected, how they are treated and which factors that influence their reliability. Off course it is the experts that are educated for this purpose, but a starting-point for the reliability-assessment model has to be developed by the decision-analyst.

This basis-model can then be expanded by the experts in roughly the same way suggested in the paragraphs above.

# 7. Conclusion

About 70 % of the value of information literature does not assess reliabilities. The remaining 30 % base their reliability-assessment on historical data, expert interviews or simulations.

In the source for a best practice in assessing reliability in 3D seismic in the exploration phase, it is useful to understand the theoretical and practical background for how the information is gathered and processed. Based on this it is possible to develop a model which connects prospect properties like faulting, dipping, depth etc. to seismic accuracy.

In this work a model has been developed to aid in the assessment of reliabilities for seismic data gathering.

The model is subjective in the sense that all the weights and the degree of presence of each of the prospect properties must be assessed by experts.

The model developed in this thesis is kept simple in an attempt to explain the concept as clearly as possible, but it is easy to expand. The same approach may also be used with other information-sources.

I have assessed the weights in the excel spreadsheet and chosen some values for the prospect properties to test if the calculated reliability-values lies somewhere in the range of what usually is assessed for seismic in exploration. The values calculated lies somewhere between 70-90 % which is consistent with values used elsewhere in the literature.

# 8. Epilogue

This work builds to a great extent on a literature study. It has given me a better understanding for the decision-analytic terminology as well as for the value of information concept.

I also notice the variation in professionals of the contributors which emphasize that decision-analysis is an interdisciplinary subject.

I will thank Olav Høiland, Specialist in Geology at Statoil ASA, for spending hours answering my questions and familiarize with the reliability-assessment model. His involvement and knowledge have been very valuable in this work.

I will also thank Øystein Arild, Decision and Risk Analysis coordinator at ConocoPhillips, for being available answering my questions, and Reidar Bratvold, Professor of Petroleum Investment & Decision Analysis at UoS, for useful feedback on this work.

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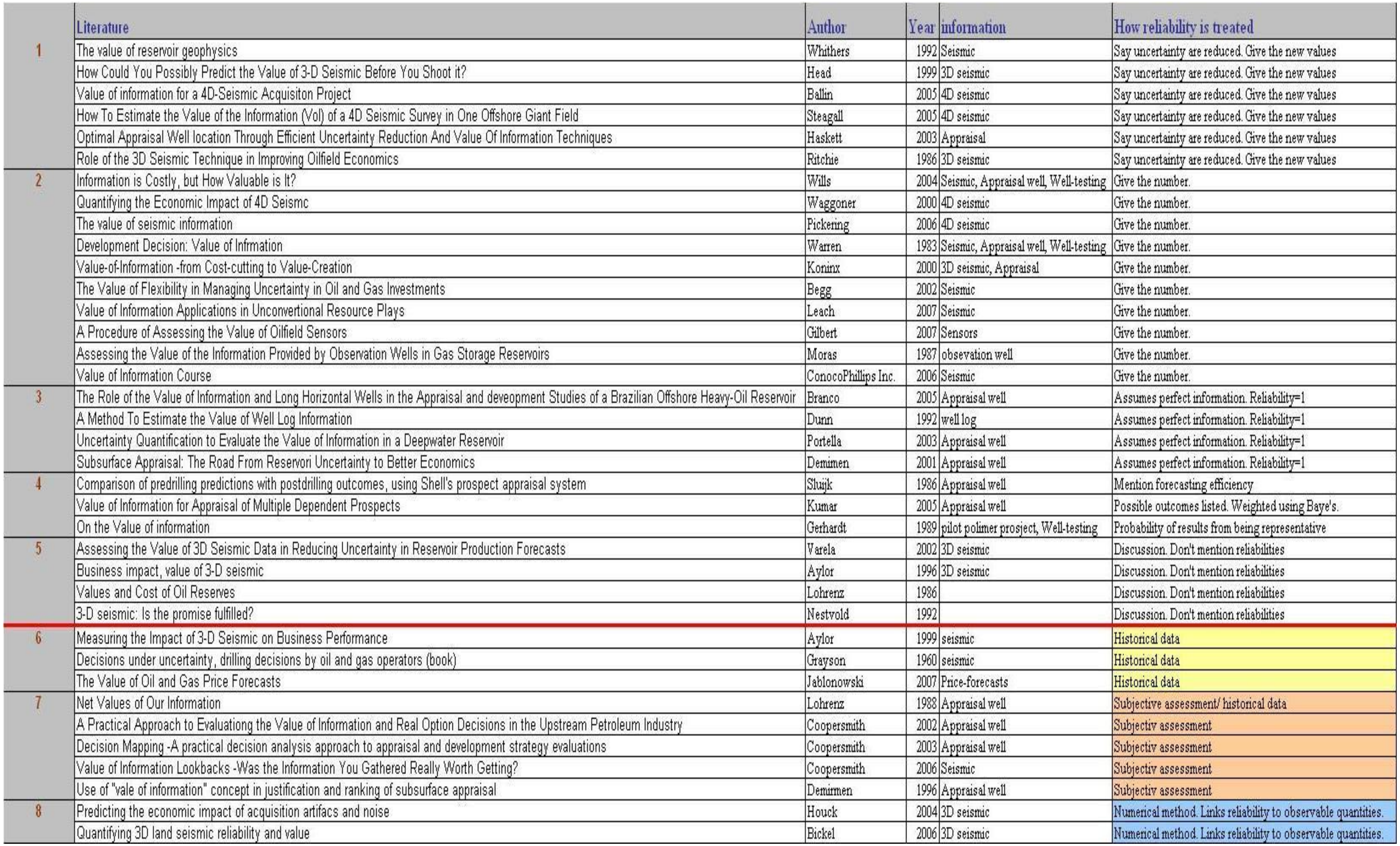
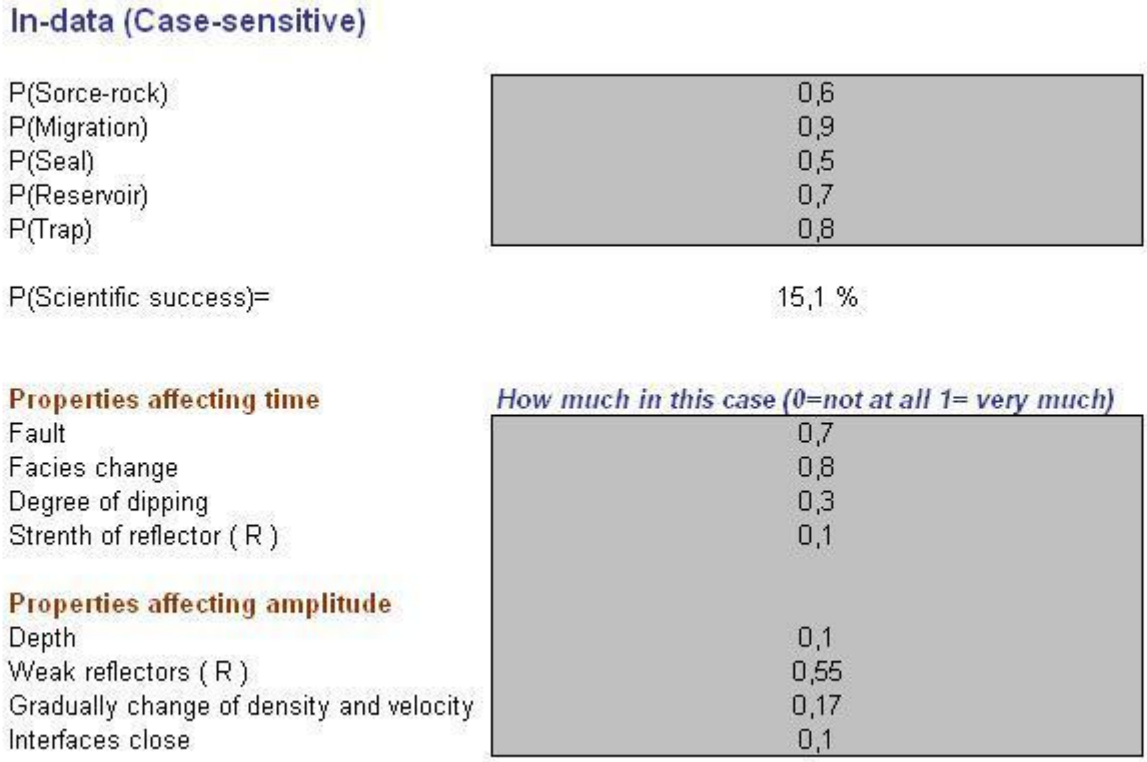
# 10. Appendix

## *A. Literature study*



| | Literature | Author | Year | information | How reliability is treated |
|---|---|---|---|---|---|
| 1 | The value of reservoir geophysics | Whithers | 1992 | Seismic | Say uncertainty are reduced. Give the new values |
| | How Could You Possibly Predict the Value of 3-D Seismic Before You Shoot it? | Head | 1999 | 3D seismic | Say uncertainty are reduced. Give the new values |
| | Value of information for a 4D-Seismic Acquisiton Project | Ballin | 2005 | 4D seismic | Say uncertainty are reduced. Give the new values |
| | How To Estimate the Value of the Information (VoI) of a 4D Seismic Survey in One Offshore Giant Field | Steagall | 2005 | 4D seismic | Say uncertainty are reduced. Give the new values |
| | Optimal Appraisal Well location Through Efficient Uncertainty Reduction And Value Of Information Techniques | Haskett | 2003 | Appraisal | Say uncertainty are reduced. Give the new values |
| | Role of the 3D Seismic Technique in Improving Oilfield Economics | Ritchie | 1986 | 3D seismic | Say uncertainty are reduced. Give the new values |
| 2 | Information is Costly, but How Valuable is It? | Wills | 2004 | Seismic, Appraisal well, Well-testing | Give the number. |
| | Quantifying the Economic Impact of 4D Seismc | Waggoner | 2000 | 4D seismic | Give the number. |
| | The value of seismic information | Pickering | 2006 | 4D seismic | Give the number. |
| | Development Decision: Value of Infrmation | Warren | 1983 | Seismic, Appraisal well, Well-testing | Give the number. |
| | Value-of-Information -from Cost-cutting to Value-Creation | Koninx | 2000 | 3D seismic, Appraisal | Give the number. |
| | The Value of Flexibility in Managing Uncertainty in Oil and Gas Investments | Begg | 2002 | Seismic | Give the number. |
| | Value of Information Applications in Unconvertional Resource Plays | Leach | 2007 | Seismic | Give the number. |
| | A Procedure of Assessing the Value of Oilfield Sensors | Gilbert | 2007 | Sensors | Give the number. |
| | Assessing the Value of the Information Provided by Observation Wells in Gas Storage Reservoirs | Moras | 1987 | obsevation well | Give the number. |
| | Value of Information Course | ConocoPhillips Inc. | 2006 | Seismic | Give the number. |
| 3 | The Role of the Value of Information and Long Horizontal Wells in the Appraisal and deveopment Studies of a Brazilian Offshore Heavy-Oil Reservoir | Branco | 2005 | Appraisal well | Assumes perfect information. Reliability=1 |
| | A Method To Estimate the Value of Well Log Information | Dunn | 1992 | well log | Assumes perfect information. Reliability=1 |
| | Uncertainty Quantification to Evaluate the Value of Information in a Deepwater Reservoir | Portella | 2003 | Appraisal well | Assumes perfect information. Reliability=1 |
| | Subsurface Appraisal: The Road From Reservori Uncertainty to Better Economics | Demirmen | 2001 | Appraisal well | Assumes perfect information. Reliability=1 |
| 4 | Comparison of predrilling predictions with postdrilling outcomes, using Shell's prospect appraisal system | Sluijk | 1986 | Appraisal well | Mention forecasting efficiency |
| | Value of Information for Appraisal of Multiple Dependent Prospects | Kumar | 2005 | Appraisal well | Possible outcomes listed. Weighted using Baye's. |
| | On the Value of information | Gerhardt | 1989 | pilot polimer prosject, Well-testing | Probability of results from being representative |
| 5 | Assessing the Value of 3D Seismic Data in Reducing Uncertainty in Reservoir Production Forecasts | Varela | 2002 | 3D seismic | Discussion. Don't mention reliabilities |
| | Business impact, value of 3-D seismic | Aylor | 1996 | 3D seismic | Discussion. Don't mention reliabilities |
| | Values and Cost of Oil Reserves | Lohrenz | 1986 | | Discussion. Don't mention reliabilities |
| | 3-D seismic: Is the promise fulfilled? | Nestvold | 1992 | | Discussion. Don't mention reliabilities |
| 6 | Measuring the Impact of 3-D Seismic on Business Performance | Aylor | 1999 | seismic | Historical data |
| | Decisions under uncertainty, drilling decisions by oil and gas operators (book) | Grayson | 1960 | seismic | Historical data |
| | The Value of Oil and Gas Price Forecasts | Jablonowski | 2007 | Price-forecasts | Historical data |
| 7 | Net Values of Our Information | Lohrenz | 1988 | Appraisal well | Subjective assessment/ historical data |
| | A Practical Approach to Evaluationg the Value of Information and Real Option Decisions in the Upstream Petroleum Industry | Coopersmith | 2002 | Appraisal well | Subjectiv assessment |
| | Decision Mapping -A practical decision analysis approach to appraisal and development strategy evaluations | Coopersmith | 2003 | Appraisal well | Subjectiv assessment |
| | Value of Information Lookbacks -Was the Information You Gathered Really Worth Getting? | Coopersmith | 2006 | Seismic | Subjectiv assessment |
| | Use of "vale of information" concept in justification and ranking of subsurface appraisal | Demirmen | 1996 | Appraisal well | Subjectiv assessment |
| 8 | Predicting the economic impact of acquisition artifacs and noise | Houck | 2004 | 3D seismic | Numerical method. Links reliability to observable quantities. |
| | Quantifying 3D land seismic reliability and value | Bickel | 2006 | 3D seismic | Numerical method. Links reliability to observable quantities. |

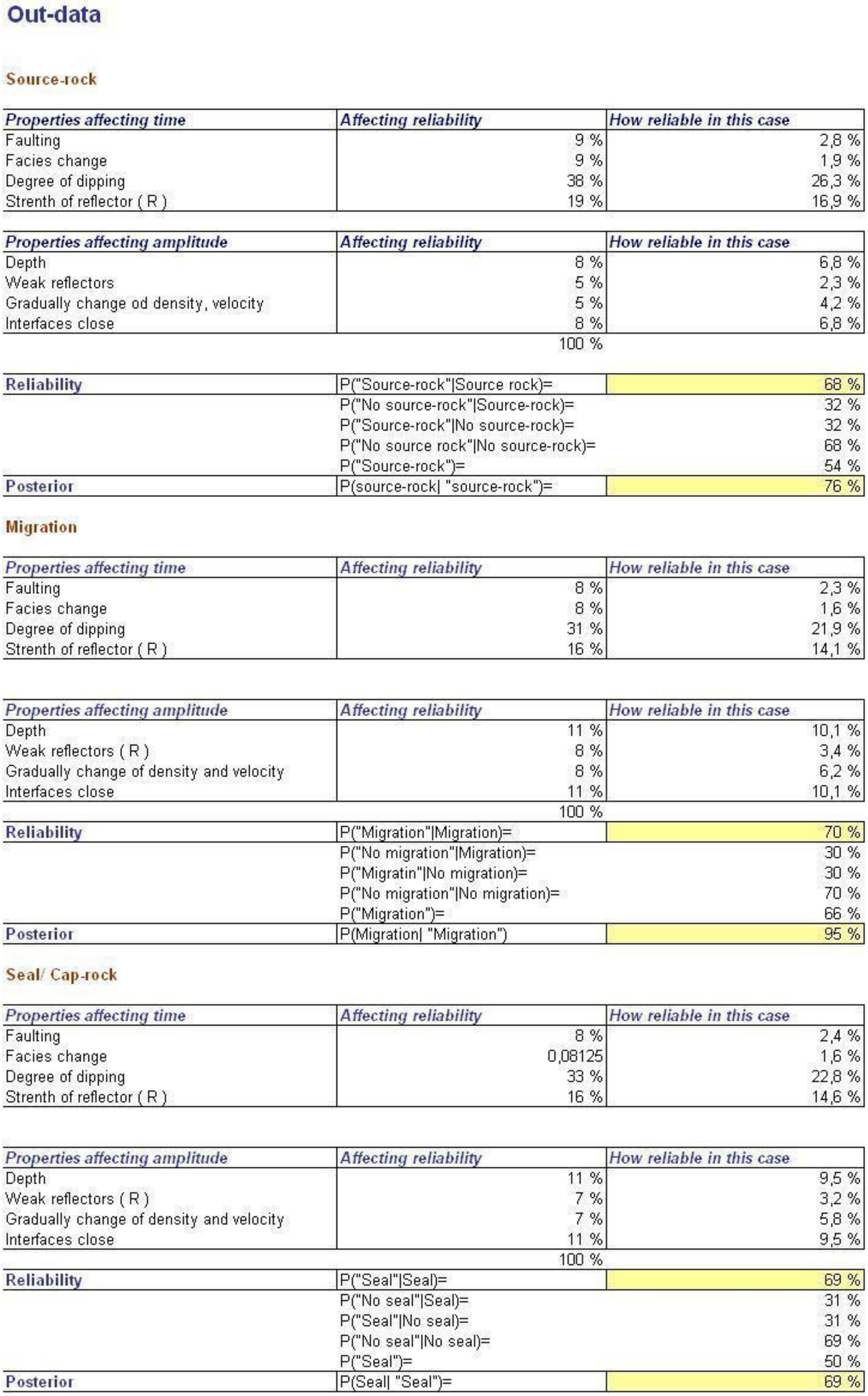
## *B. Spreadsheet-model calculations*



### In-data (Case-sensitive)

| | |
|---|---|
| P(Sorce-rock) | 0,6 |
| P(Migration) | 0,9 |
| P(Seal) | 0,5 |
| P(Reservoir) | 0,7 |
| P(Trap) | 0,8 |
| | |
| P(Scientific success)= | 15,1 % |

| **Properties affecting time** | *How much in this case (0=not at all 1= very much)* |
|---|---|
| Fault | 0,7 |
| Facies change | 0,8 |
| Degree of dipping | 0,3 |
| Strenth of reflector ( R ) | 0,1 |
| | |
| **Properties affecting amplitude** | |
| Depth | 0,1 |
| Weak reflectors ( R ) | 0,55 |
| Gradually change of density and velocity | 0,17 |
| Interfaces close | 0,1 |



## Out-data

### Source-rock

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Faulting | 9 % | 2,8 % |
| Facies change | 9 % | 1,9 % |
| Degree of dipping | 38 % | 26,3 % |
| Strenth of reflector ( R ) | 19 % | 16,9 % |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | 8 % | 6,8 % |
| Weak reflectors | 5 % | 2,3 % |
| Gradually change od density, velocity | 5 % | 4,2 % |
| Interfaces close | 8 % | 6,8 % |
| | 100 % | |

| | | |
|---|---|---|
| **Reliability** | P("Source-rock"\|Source rock)= | 68 % |
| | P("No source-rock"\|Source-rock)= | 32 % |
| | P("Source-rock"\|No source-rock)= | 32 % |
| | P("No source rock"\|No source-rock)= | 68 % |
| | P("Source-rock")= | 54 % |
| **Posterior** | P(source-rock\| "source-rock")= | 76 % |

### Migration

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Faulting | 8 % | 2,3 % |
| Facies change | 8 % | 1,6 % |
| Degree of dipping | 31 % | 21,9 % |
| Strenth of reflector ( R ) | 16 % | 14,1 % |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | 11 % | 10,1 % |
| Weak reflectors ( R ) | 8 % | 3,4 % |
| Gradually change of density and velocity | 8 % | 6,2 % |
| Interfaces close | 11 % | 10,1 % |
| | 100 % | |

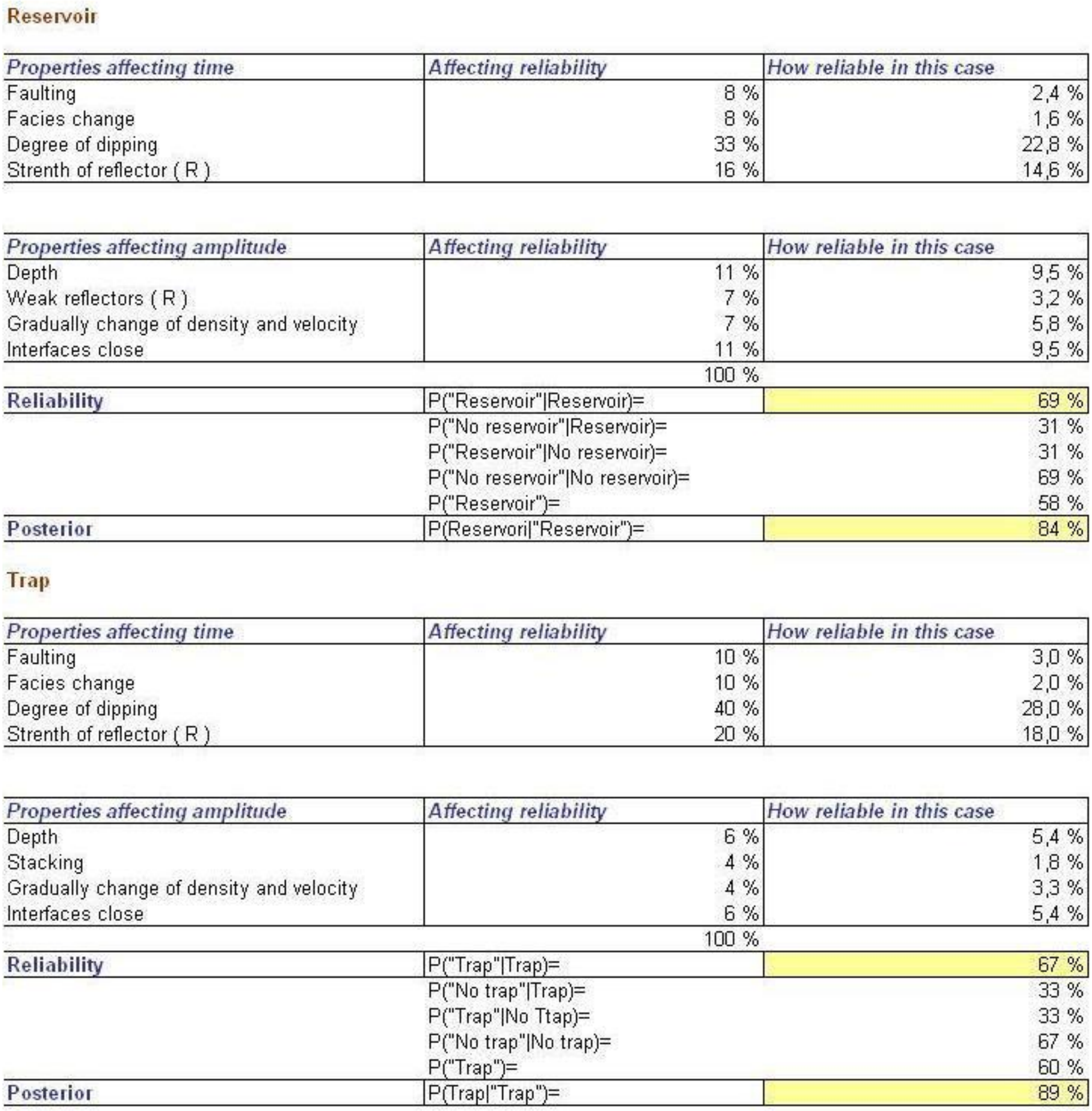
| | | |
|---|---|---|
| **Reliability** | P("Migration"\|Migration)= | 70 % |
| | P("No migration"\|Migration)= | 30 % |
| | P("Migratin"\|No migration)= | 30 % |
| | P("No migration"\|No migration)= | 70 % |
| | P("Migration")= | 66 % |
| **Posterior** | P(Migration\| "Migration") | 95 % |

### Seal/ Cap-rock

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Faulting | 8 % | 2,4 % |
| Facies change | 0,08125 | 1,6 % |
| Degree of dipping | 33 % | 22,8 % |
| Strenth of reflector ( R ) | 16 % | 14,6 % |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | 11 % | 9,5 % |
| Weak reflectors ( R ) | 7 % | 3,2 % |
| Gradually change of density and velocity | 7 % | 5,8 % |
| Interfaces close | 11 % | 9,5 % |
| | 100 % | |

| | | |
|---|---|---|
| **Reliability** | P("Seal"\|Seal)= | 69 % |
| | P("No seal"\|Seal)= | 31 % |
| | P("Seal"\|No seal)= | 31 % |
| | P("No seal"\|No seal)= | 69 % |
| | P("Seal")= | 50 % |
| **Posterior** | P(Seal\| "Seal")= | 69 % |



**Reservoir**

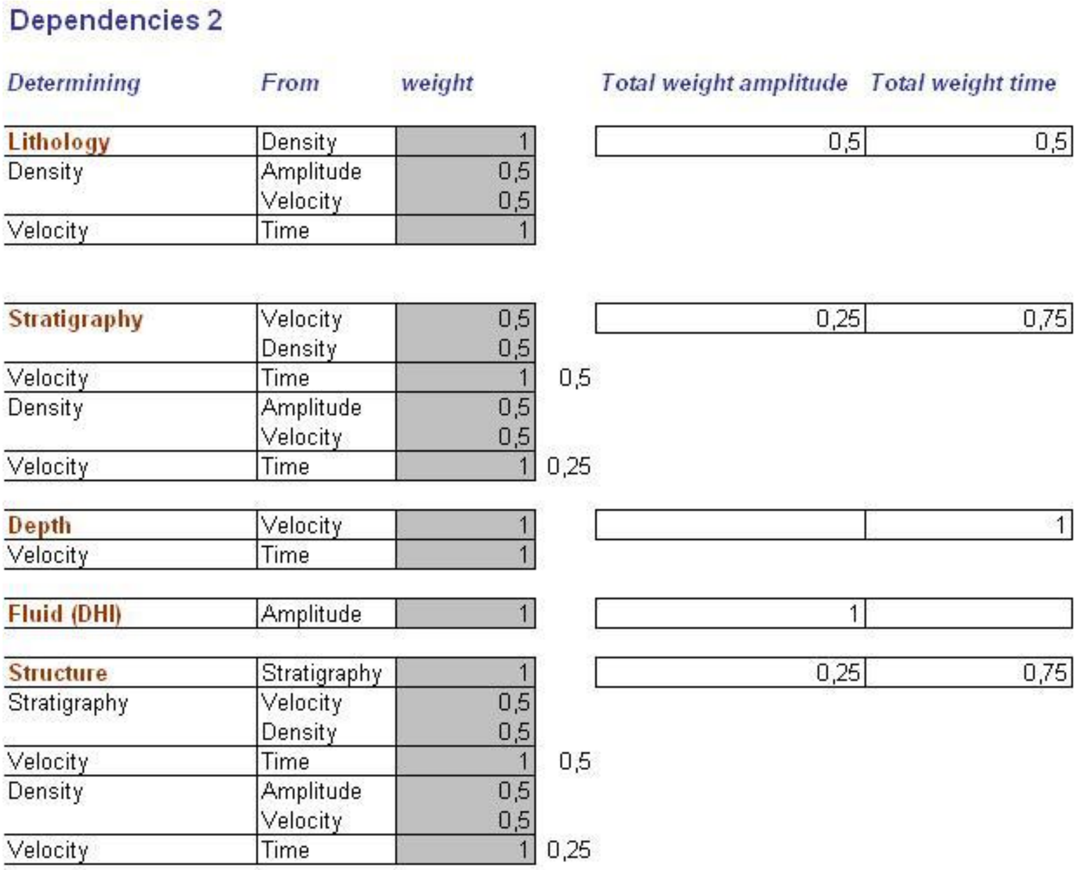
| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Faulting | 8 % | 2,4 % |
| Facies change | 8 % | 1,6 % |
| Degree of dipping | 33 % | 22,8 % |
| Strenth of reflector ( R ) | 16 % | 14,6 % |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | 11 % | 9,5 % |
| Weak reflectors ( R ) | 7 % | 3,2 % |
| Gradually change of density and velocity | 7 % | 5,8 % |
| Interfaces close | 11 % | 9,5 % |
|  | 100 % |  |
| **Reliability** | P("Reservoir"\|Reservoir)= | 69 % |
|  | P("No reservoir"\|Reservoir)= | 31 % |
|  | P("Reservoir"\|No reservoir)= | 31 % |
|  | P("No reservoir"\|No reservoir)= | 69 % |
|  | P("Reservoir")= | 58 % |
| **Posterior** | P(Reservori\|"Reservoir")= | 84 % |

**Trap**

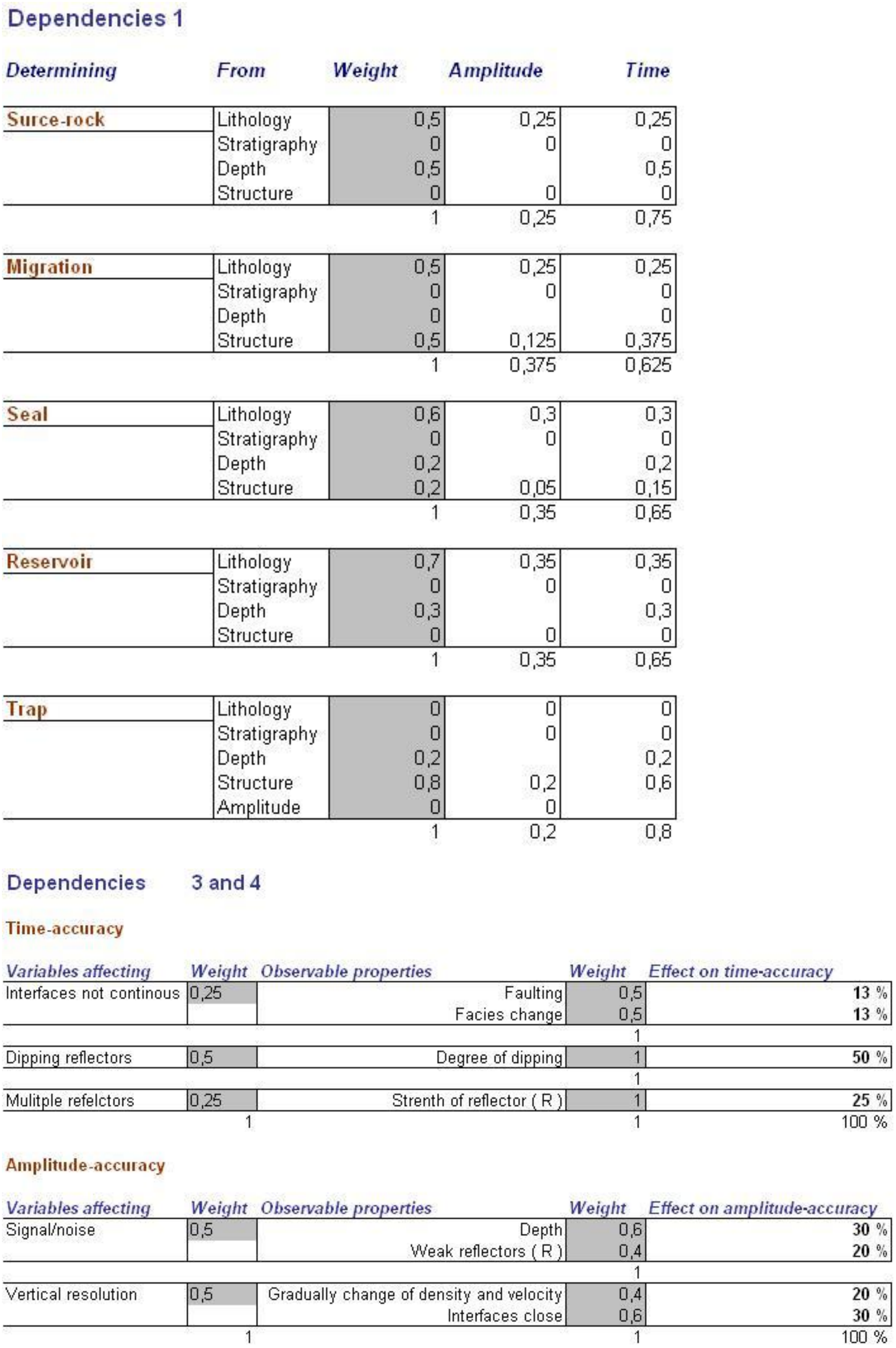
| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Faulting | 10 % | 3,0 % |
| Facies change | 10 % | 2,0 % |
| Degree of dipping | 40 % | 28,0 % |
| Strenth of reflector ( R ) | 20 % | 18,0 % |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | 6 % | 5,4 % |
| Stacking | 4 % | 1,8 % |
| Gradually change of density and velocity | 4 % | 3,3 % |
| Interfaces close | 6 % | 5,4 % |
|  | 100 % |  |
| **Reliability** | P("Trap"\|Trap)= | 67 % |
|  | P("No trap"\|Trap)= | 33 % |
|  | P("Trap"\|No Ttap)= | 33 % |
|  | P("No trap"\|No trap)= | 67 % |
|  | P("Trap")= | 60 % |
| **Posterior** | P(Trap\|"Trap")= | 89 % |



## Dependencies 2

| *Determining* | *From* | *weight* | | *Total weight amplitude* | *Total weight time* |
|---|---|---|---|---|---|
| **Lithology** | Density | 1 | | 0,5 | 0,5 |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | | | |
| **Stratigraphy** | Velocity | 0,5 | | 0,25 | 0,75 |
| | Density | 0,5 | | | |
| Velocity | Time | 1 | 0,5 | | |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | 0,25 | | |
| **Depth** | Velocity | 1 | | | 1 |
| Velocity | Time | 1 | | | |
| **Fluid (DHI)** | Amplitude | 1 | | 1 | |
| **Structure** | Stratigraphy | 1 | | 0,25 | 0,75 |
| Stratigraphy | Velocity | 0,5 | | | |
| | Density | 0,5 | | | |
| Velocity | Time | 1 | 0,5 | | |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | 0,25 | | |



## Dependencies 1

| *Determining* | *From* | *Weight* | *Amplitude* | *Time* |
|---|---|---|---|---|
| **Surce-rock** | Lithology | 0,5 | 0,25 | 0,25 |
| | Stratigraphy | 0 | 0 | 0 |
| | Depth | 0,5 | | 0,5 |
| | Structure | 0 | 0 | 0 |
| | | 1 | 0,25 | 0,75 |
| **Migration** | Lithology | 0,5 | 0,25 | 0,25 |
| | Stratigraphy | 0 | 0 | 0 |
| | Depth | 0 | | 0 |
| | Structure | 0,5 | 0,125 | 0,375 |
| | | 1 | 0,375 | 0,625 |
| **Seal** | Lithology | 0,6 | 0,3 | 0,3 |
| | Stratigraphy | 0 | 0 | 0 |
| | Depth | 0,2 | | 0,2 |
| | Structure | 0,2 | 0,05 | 0,15 |
| | | 1 | 0,35 | 0,65 |
| **Reservoir** | Lithology | 0,7 | 0,35 | 0,35 |
| | Stratigraphy | 0 | 0 | 0 |
| | Depth | 0,3 | | 0,3 |
| | Structure | 0 | 0 | 0 |
| | | 1 | 0,35 | 0,65 |
| **Trap** | Lithology | 0 | 0 | 0 |
| | Stratigraphy | 0 | 0 | 0 |
| | Depth | 0,2 | | 0,2 |
| | Structure | 0,8 | 0,2 | 0,6 |
| | Amplitude | 0 | 0 | |
| | | 1 | 0,2 | 0,8 |

## Dependencies 3 and 4

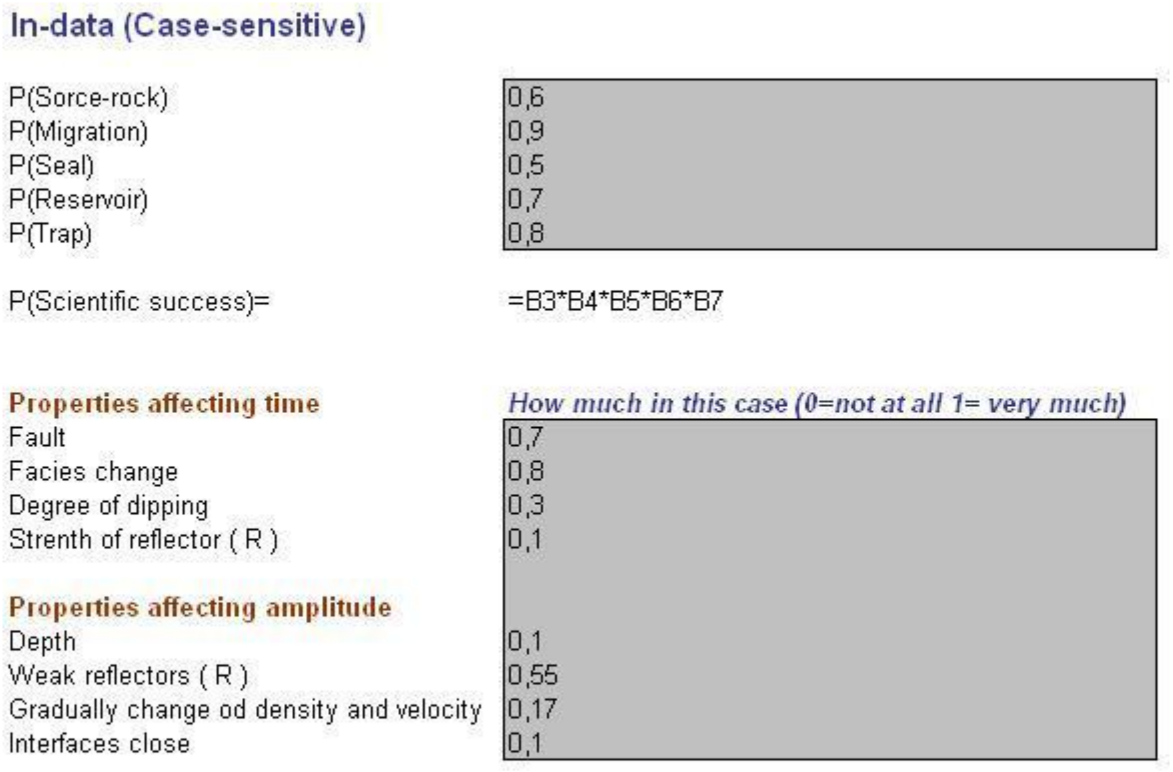
### Time-accuracy

| *Variables affecting* | *Weight* | *Observable properties* | *Weight* | *Effect on time-accuracy* |
|---|---|---|---|---|
| Interfaces not continous | 0,25 | Faulting | 0,5 | **13** % |
| | | Facies change | 0,5 | **13** % |
| | | | 1 | |
| Dipping reflectors | 0,5 | Degree of dipping | 1 | **50** % |
| | | | 1 | |
| Mulitple refelctors | 0,25 | Strenth of reflector ( R ) | 1 | **25** % |
| | 1 | | 1 | 100 % |

### Amplitude-accuracy

| *Variables affecting* | *Weight* | *Observable properties* | *Weight* | *Effect on amplitude-accuracy* |
|---|---|---|---|---|
| Signal/noise | 0,5 | Depth | 0,6 | **30** % |
| | | Weak reflectors ( R ) | 0,4 | **20** % |
| | | | 1 | |
| Vertical resolution | 0,5 | Gradually change of density and velocity | 0,4 | **20** % |
| | | Interfaces close | 0,6 | **30** % |
| | 1 | | 1 | 100 % |

## C. Spreadsheet-model formulas



In-data (Case-sensitive)

| | |
|---|---|
| P(Sorce-rock) | 0,6 |
| P(Migration) | 0,9 |
| P(Seal) | 0,5 |
| P(Reservoir) | 0,7 |
| P(Trap) | 0,8 |
| | |
| P(Scientific success)= | =B3*B4*B5*B6*B7 |

| Properties affecting time | How much in this case (0=not at all 1= very much) |
|---|---|
| Fault | 0,7 |
| Facies change | 0,8 |
| Degree of dipping | 0,3 |
| Strenth of reflector ( R ) | 0,1 |
| | |
| **Properties affecting amplitude** | |
| Depth | 0,1 |
| Weak reflectors ( R ) | 0,55 |
| Gradually change od density and velocity | 0,17 |
| Interfaces close | 0,1 |

## Out-data

### Source-rock

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Fault | ='Dependencies 1'!E9*'Dependencies 3 and 4'!E6 | =B7-('In-data '!B13*B7) |
| Facies change | ='Dependencies 1'!E9*'Dependencies 3 and 4'!E7 | =B8-('In-data '!B14*B8) |
| Degree of dipping | ='Dependencies 1'!E9*'Dependencies 3 and 4'!E9 | =B9-('In-data '!B15*B9) |
| Strenth of reflector ( R ) | ='Dependencies 1'!E9*'Dependencies 3 and 4'!E11 | =B10-('In-data '!B16*B10) |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | ='Dependencies 1'!D5*'Dependencies 3 and 4'!E17 | =B13-('In-data '!B19*B13) |
| Weak reflectors ( R ) | ='Dependencies 1'!D5*'Dependencies 3 and 4'!E18 | =B14-('In-data '!B20*B14) |
| Gradually change od density, velocity | ='Dependencies 1'!D5*'Dependencies 3 and 4'!E20 | =B15-('In-data '!B21*B15) |
| Interfaces close | ='Dependencies 1'!D5*'Dependencies 3 and 4'!E21 | =B16-('In-data '!B22*B16) |
|  | =SUMMER(B7:B16) |  |

| | | |
|---|---|---|
| **Reliability** | P("Source-rock"\|Source-rock)= | =SUMMER(C7:C16) |
|  | P("No source-rock"\|Source-rock)= | =1-C19 |
|  | P("Source-rock"\|No source-rock)= | =1-C22 |
|  | P("No source rock"\|No source-rock)= | =C19 |
|  | P("Source-rock")= | =C19*'In-data '!B3+C21*(1-'In-data '!B3) |
| **Posterior** | P(Source-rock\| "Source-rock")= | =C19*'In-data '!B3/'Out-data'!C23 |

### Migration

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Fault | ='Dependencies 1'!E15*'Dependencies 3 and 4'!E6 | =B40-('In-data '!B13*B40) |
| Facies change | ='Dependencies 1'!E15*'Dependencies 3 and 4'!E7 | =B41-('In-data '!B14*B41) |
| Degree of dipping | ='Dependencies 1'!E15*'Dependencies 3 and 4'!E9 | =B42-('In-data '!B15*B42) |
| Strenth of reflector ( R ) | ='Dependencies 1'!E15*'Dependencies 3 and 4'!E11 | =B43-('In-data '!B16*B43) |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | ='Dependencies 1'!D15*'Dependencies 3 and 4'!E17 | =B49-('In-data '!B19*B49) |
| Weak reflectors ( R ) | ='Dependencies 1'!D15*'Dependencies 3 and 4'!E18 | =B50-('In-data '!B20*B50) |
| Gradually change od density, velocity | ='Dependencies 1'!D15*'Dependencies 3 and 4'!E20 | =B51-('In-data '!B21*B51) |
| Interfaces close | ='Dependencies 1'!D15*'Dependencies 3 and 4'!E21 | =B52-('In-data '!B22*B52) |
|  | =SUMMER(B40:B52) |  |
| **Reliability** | P("migration"\|migration)= | =SUMMER(C40:C52) |
|  | P("no migration"\|migration)= | =1-C54 |
|  | P("migratin"\|no migration)= | =1-C57 |
|  | P("no migration"\|no migration)= | =C54 |
|  | P("migration")= | =C54*'In-data '!B4+'Out-data'!C56*(1-'In-data '!B4) |
| **Posterior** | P(migration\| "migration") | =C54*'In-data '!B4/'Out-data'!C58 |

### Seal/ Cap-rock

| *Properties affecting time* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Fault | ='Dependencies 1'!E21*'Dependencies 3 and 4'!E6 | =B76-('In-data '!B13*B76) |
| Facies change | ='Dependencies 1'!E21*'Dependencies 3 and 4'!E7 | =B77-('In-data '!B14*B77) |
| Degree of dipping | ='Dependencies 1'!E21*'Dependencies 3 and 4'!E9 | =B78-('In-data '!B15*B78) |
| Strenth of reflector ( R ) | ='Dependencies 1'!E21*'Dependencies 3 and 4'!E11 | =B79-('In-data '!B16*B79) |

| *Properties affecting amplitude* | *Affecting reliability* | *How reliable in this case* |
|---|---|---|
| Depth | ='Dependencies 1'!D21*'Dependencies 3 and 4'!E17 | =B83-('In-data '!B19*B83) |
| Weak reflectors ( R ) | ='Dependencies 1'!D21*'Dependencies 3 and 4'!E18 | =B84-('In-data '!B20*B84) |
| Gradually change od density, velocity | ='Dependencies 1'!D21*'Dependencies 3 and 4'!E20 | =B85-('In-data '!B21*B85) |
| Interfaces close | ='Dependencies 1'!D21*'Dependencies 3 and 4'!E21 | =B86-('In-data '!B22*B86) |
|  | =SUMMER(B76:B86) |  |
| **Reliability** | P("seal"\|seal)= | =SUMMER(C76:C86) |
|  | P("no seal"\|seal)= | =1-C88 |
|  | P("seal"\|not seal)= | =1-C91 |
|  | P("no seal"\|no seal)= | =C88 |
|  | P("seal")= | =C88*'In-data '!B5+'Out-data'!C90*(1-'In-data '!B5) |
| **Posterior** | P(seal\| "seal")= | =C88*'In-data '!B5/'Out-data'!C92 |

## Reservoir

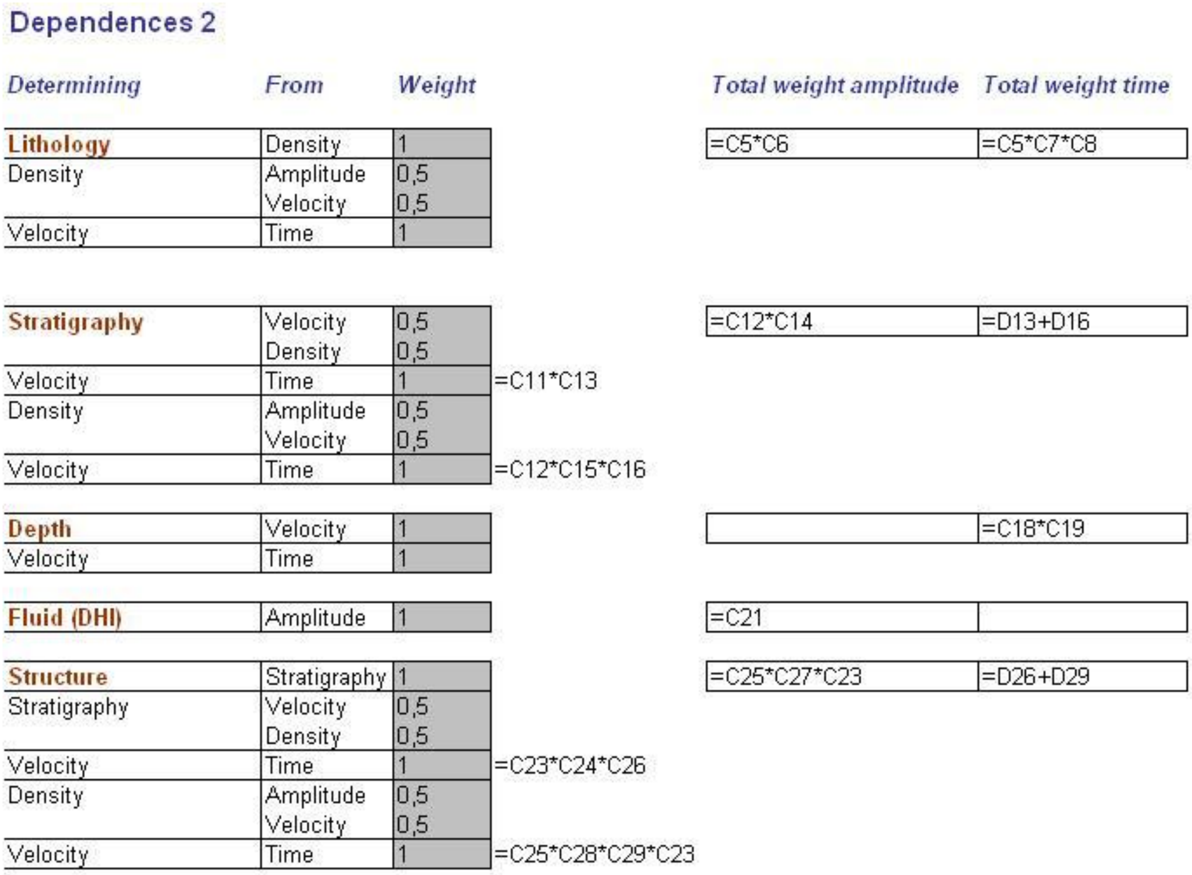
| Properties affecting time | Affecting reliability | How reliable in this case |
|---|---|---|
| Fault | ='Dependencies 1'!E27*'Dependencies 3 and 4'!E6 | =B112-('In-data '!B13*B112) |
| Facies change | ='Dependencies 1'!E27*'Dependencies 3 and 4'!E7 | =B113-('In-data '!B14*B113) |
| Degree of dipping | ='Dependencies 1'!E27*'Dependencies 3 and 4'!E9 | =B114-('In-data '!B15*B114) |
| Strenth of reflector ( R ) | ='Dependencies 1'!E27*'Dependencies 3 and 4'!E11 | =B115-('In-data '!B16*B115) |

| Properties affecting amplitude | Affecting reliability | How reliable in this case |
|---|---|---|
| Depth | ='Dependencies 1'!D27*'Dependencies 3 and 4'!E17 | =B119-('In-data '!B19*B119) |
| Weak reflectors ( R ) | ='Dependencies 1'!D27*'Dependencies 3 and 4'!E18 | =B120-('In-data '!B20*B120) |
| Gradually change od density, velocity | ='Dependencies 1'!D27*'Dependencies 3 and 4'!E20 | =B121-('In-data '!B21*B121) |
| Interfaces close | ='Dependencies 1'!D27*'Dependencies 3 and 4'!E21 | =B122-('In-data '!B22*B122) |
|  | =SUMMER(B112:B122) |  |
| **Reliability** | P("reservoir"\|reservoir)= | =SUMMER(C112:C122) |
|  | P("no reservoir"\|reservoir)= | =1-C124 |
|  | P("reservoir"\|no reservoir)= | =1-C127 |
|  | P("no reservoir"\|no reservoir)= | =C124 |
|  | P("reservoir")= | =C124*'In-data '!B6+'Out-data'!C126*(1-'In-data '!B6) |
| **Posterior** | P(reservori\|"reservoir")= | =C124*'In-data '!B6/'Out-data'!C128 |

## Trap

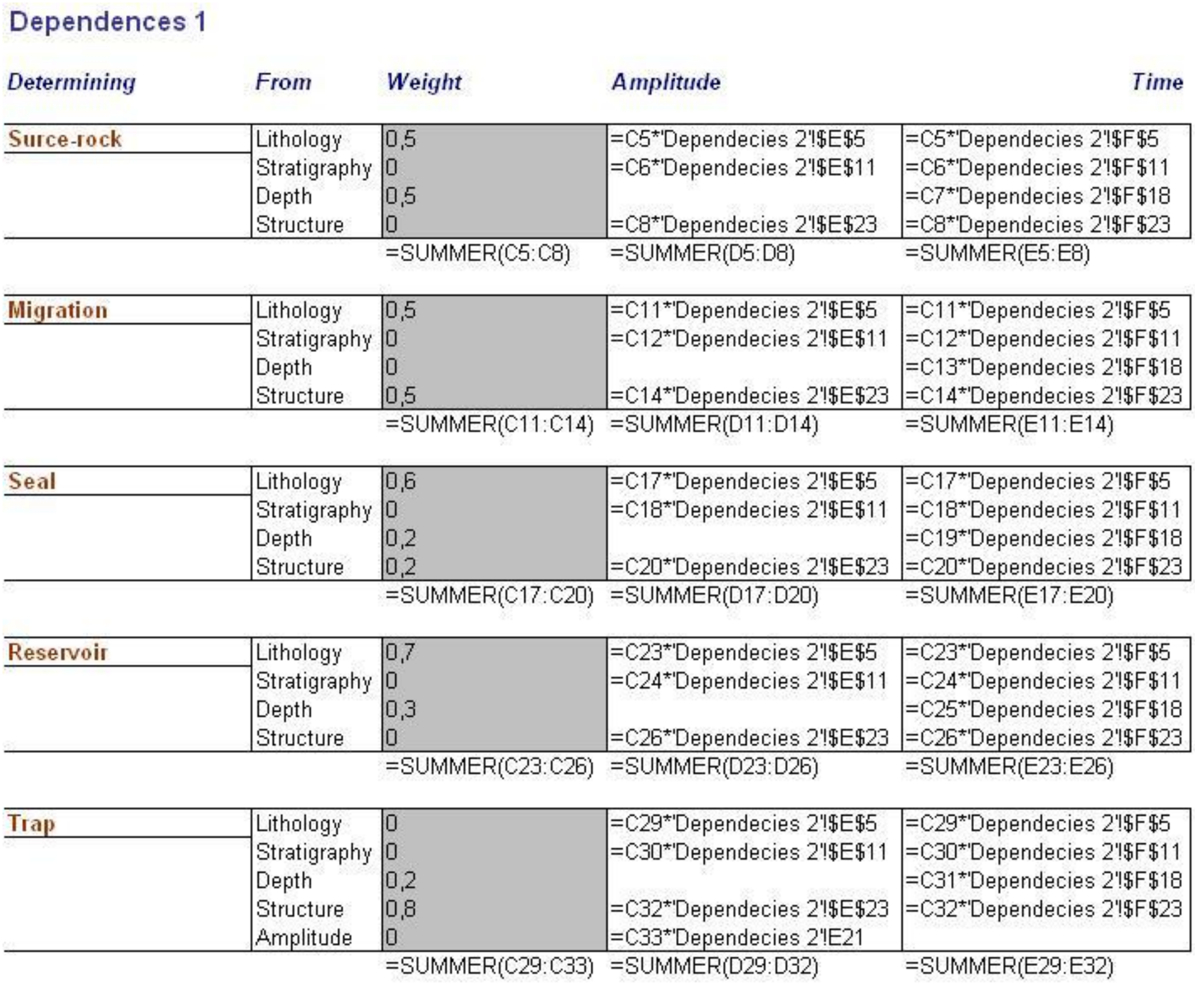
| Properties affecting time | Affecting reliability | How reliable in this case |
|---|---|---|
| Fault | ='Dependencies 1'!E34*'Dependencies 3 and 4'!E6 | =B148-('In-data '!B13*B148) |
| Facies change | ='Dependencies 1'!E34*'Dependencies 3 and 4'!E7 | =B149-('In-data '!B14*B149) |
| Degree of dipping | ='Dependencies 1'!E34*'Dependencies 3 and 4'!E9 | =B150-('In-data '!B15*B150) |
| Strenth of reflector ( R ) | ='Dependencies 1'!E34*'Dependencies 3 and 4'!E11 | =B151-('In-data '!B16*B151) |

| Properties affecting amplitude | Affecting reliability | How reliable in this case |
|---|---|---|
| Depth | ='Dependencies 1'!D34*'Dependencies 3 and 4'!E17 | =B155-('In-data '!B19*B155) |
| Weak reflectors ( R ) | ='Dependencies 1'!D34*'Dependencies 3 and 4'!E18 | =B156-('In-data '!B20*B156) |
| Gradually change od density, velocity | ='Dependencies 1'!D34*'Dependencies 3 and 4'!E20 | =B157-('In-data '!B21*B157) |
| Interfaces close | ='Dependencies 1'!D34*'Dependencies 3 and 4'!E21 | =B158-('In-data '!B22*B158) |
|  | =SUMMER(B148:B158) |  |
| **Reliability** | P("Trap"\|Trap)= | =SUMMER(C148:C158) |
|  | P("no Trap"\|Trap)= | =1-C160 |
|  | P("Trap"\|no Trap)= | =1-C163 |
|  | P("no Trap"\|no Trap)= | =C160 |
|  | P("trap")= | =C160*'In-data '!B7+'Out-data'!C162*(1-'In-data '!B7) |
| **Posterior** | P(Trap\|"Trap")= | =C160*'In-data '!B7/'Out-data'!C164 |



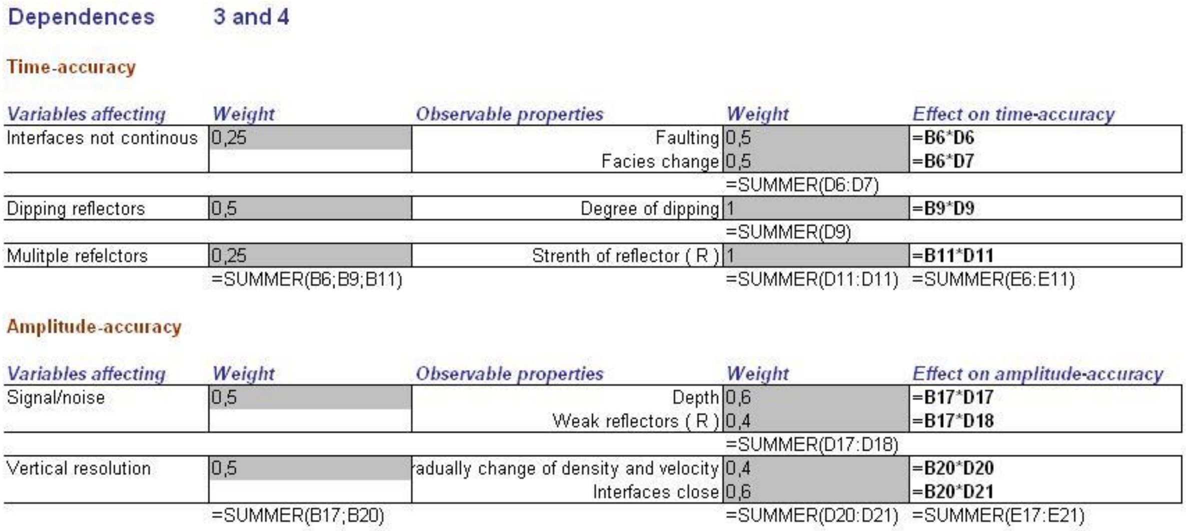
## Dependences 2

| *Determining* | *From* | *Weight* | | *Total weight amplitude* | *Total weight time* |
|---|---|---|---|---|---|
| **Lithology** | Density | 1 | | =C5*C6 | =C5*C7*C8 |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | | | |
| | | | | | |
| **Stratigraphy** | Velocity | 0,5 | | =C12*C14 | =D13+D16 |
| | Density | 0,5 | | | |
| Velocity | Time | 1 | =C11*C13 | | |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | =C12*C15*C16 | | |
| **Depth** | Velocity | 1 | | | =C18*C19 |
| Velocity | Time | 1 | | | |
| **Fluid (DHI)** | Amplitude | 1 | | =C21 | |
| **Structure** | Stratigraphy | 1 | | =C25*C27*C23 | =D26+D29 |
| Stratigraphy | Velocity | 0,5 | | | |
| | Density | 0,5 | | | |
| Velocity | Time | 1 | =C23*C24*C26 | | |
| Density | Amplitude | 0,5 | | | |
| | Velocity | 0,5 | | | |
| Velocity | Time | 1 | =C25*C28*C29*C23 | | |



## Dependences 1

| *Determining* | *From* | *Weight* | *Amplitude* | *Time* |
|---|---|---|---|---|
| **Surce-rock** | Lithology | 0,5 | =C5*Dependecies 2'!$E$5 | =C5*Dependecies 2'!$F$5 |
| | Stratigraphy | 0 | =C6*Dependecies 2'!$E$11 | =C6*Dependecies 2'!$F$11 |
| | Depth | 0,5 | | =C7*Dependecies 2'!$F$18 |
| | Structure | 0 | =C8*Dependecies 2'!$E$23 | =C8*Dependecies 2'!$F$23 |
| | | =SUMMER(C5:C8) | =SUMMER(D5:D8) | =SUMMER(E5:E8) |
| **Migration** | Lithology | 0,5 | =C11*Dependecies 2'!$E$5 | =C11*Dependecies 2'!$F$5 |
| | Stratigraphy | 0 | =C12*Dependecies 2'!$E$11 | =C12*Dependecies 2'!$F$11 |
| | Depth | 0 | | =C13*Dependecies 2'!$F$18 |
| | Structure | 0,5 | =C14*Dependecies 2'!$E$23 | =C14*Dependecies 2'!$F$23 |
| | | =SUMMER(C11:C14) | =SUMMER(D11:D14) | =SUMMER(E11:E14) |
| **Seal** | Lithology | 0,6 | =C17*Dependecies 2'!$E$5 | =C17*Dependecies 2'!$F$5 |
| | Stratigraphy | 0 | =C18*Dependecies 2'!$E$11 | =C18*Dependecies 2'!$F$11 |
| | Depth | 0,2 | | =C19*Dependecies 2'!$F$18 |
| | Structure | 0,2 | =C20*Dependecies 2'!$E$23 | =C20*Dependecies 2'!$F$23 |
| | | =SUMMER(C17:C20) | =SUMMER(D17:D20) | =SUMMER(E17:E20) |
| **Reservoir** | Lithology | 0,7 | =C23*Dependecies 2'!$E$5 | =C23*Dependecies 2'!$F$5 |
| | Stratigraphy | 0 | =C24*Dependecies 2'!$E$11 | =C24*Dependecies 2'!$F$11 |
| | Depth | 0,3 | | =C25*Dependecies 2'!$F$18 |
| | Structure | 0 | =C26*Dependecies 2'!$E$23 | =C26*Dependecies 2'!$F$23 |
| | | =SUMMER(C23:C26) | =SUMMER(D23:D26) | =SUMMER(E23:E26) |
| **Trap** | Lithology | 0 | =C29*Dependecies 2'!$E$5 | =C29*Dependecies 2'!$F$5 |
| | Stratigraphy | 0 | =C30*Dependecies 2'!$E$11 | =C30*Dependecies 2'!$F$11 |
| | Depth | 0,2 | | =C31*Dependecies 2'!$F$18 |
| | Structure | 0,8 | =C32*Dependecies 2'!$E$23 | =C32*Dependecies 2'!$F$23 |
| | Amplitude | 0 | =C33*Dependecies 2'!E21 | |
| | | =SUMMER(C29:C33) | =SUMMER(D29:D32) | =SUMMER(E29:E32) |



## Dependences 3 and 4

### Time-accuracy

| *Variables affecting* | *Weight* | *Observable properties* | *Weight* | *Effect on time-accuracy* |
|---|---|---|---|---|
| Interfaces not continous | 0,25 | Faulting | 0,5 | **=B6*D6** |
| | | Facies change | 0,5 | **=B6*D7** |
| | | | =SUMMER(D6:D7) | |
| Dipping reflectors | 0,5 | Degree of dipping | 1 | **=B9*D9** |
| | | | =SUMMER(D9) | |
| Mulitple refelctors | 0,25 | Strenth of reflector ( R ) | 1 | **=B11*D11** |
| | =SUMMER(B6;B9;B11) | | =SUMMER(D11:D11) | =SUMMER(E6:E11) |

### Amplitude-accuracy

| *Variables affecting* | *Weight* | *Observable properties* | *Weight* | *Effect on amplitude-accuracy* |
|---|---|---|---|---|
| Signal/noise | 0,5 | Depth | 0,6 | **=B17*D17** |
| | | Weak reflectors ( R ) | 0,4 | **=B17*D18** |
| | | | =SUMMER(D17:D18) | |
| Vertical resolution | 0,5 | adually change of density and velocity | 0,4 | **=B20*D20** |
| | | Interfaces close | 0,6 | **=B20*D21** |
| | =SUMMER(B17;B20) | | =SUMMER(D20:D21) | =SUMMER(E17:E21) |