

QUANTIFICATION OF PRODUCTION RISK IN THE UNDERGROUND MINE PLANNING PROCESS

by

LIZEL DOWLING

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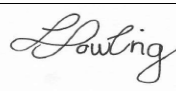
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Executive Summary

This report investigates the impact of the stoneworks process at a leading underground colliery in South Africa, which for the purpose of this report, is referred to as ABC Colliery. ABC Colliery delivers the coal to a company, which for the purpose of this report, is referred to as company XYZ.

As ABC colliery reaches depletion and the available coal reserves become limited, the flexibility of operations becomes more constrained. The production section is restricted with regard to continued coal extraction the moment it reaches a large amount of dolerite intrusion (dyke or sill) and burnt coal. This dolerite intrusion requires the intervention of a stoneworks team before any operational activities can continue. This specialised stoneworks team will be responsible for removing the dyke through blasting techniques, whereafter the production section can continue with normal coal extraction. If possible the production section starts working on another area while the stoneworks team removes the dyke. The production section will come to a standstill if the dolerite is not removed within a short period of time by the stoneworks team. The coordination of the production and stoneworks schedules is critical to prevent standstills, which will result in production losses.

Encountering of an unforeseen dyke or sill has different risks. In such a case there are two possible consequences. The first is the safety impact factor. If there is burnt coal present, there is a possibility of a safety hazard. The second impact factor is the loss of time, resulting in the loss of production volumes. The first aspect to consider with the impact on production volumes, is whether there could be space available for alternative mining if an unforeseen dyke is reached, also known as pit room. The dyke must be removed immediately by the stoneworks team if a pit room is not available. The time required to remove the dyke depends on the dyke thickness. The risk of an unforeseen dyke can be minimised by drilling more vertical or horizontal boreholes in order to attain a more accurate position of the dolerite intrusions. This more perfect information results in a trade-off between higher costs and more accurate information that will significantly reduce the risks of the safety impact and production volumes.

The value of imperfect information is reflected in the uncertainty of an unforeseen dyke. A decision tree model was built with the possibilities and probabilities of actual events in the past to determine the value of imperfect information. A Monte Carlo simulation was

computed by using the triangular distribution for the input variables. A sensitivity analysis was performed to determine the input values with the highest impact on the expected value of R 65 million. From the analysis it was clear that the expected value was most sensitive to the availability of pit room.

The value of R 65 million generated by the model indicates the risks to the process as a result of an unforeseen dyke or sill. It now becomes a business decision to determine how much will be utilised to reduce the risk. This decision is based on economic requirements and the level of risk avoidance practised by the company. The funds can be allocated to different areas to obtain more perfect information and / or to optimise the production, stoneworks and geological exploration processes.

The actual amount of drilling is R8 million per year. This represents only 12% of the calculated risk and is a function of the economic considerations and risk avoidance practices as mentioned above. The optimisation of this amount and the allocation thereof were not part of this project and provide good opportunities for further development and future projects.

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Chapter 1: Introduction

1.1 Problem Background

1.1.1 Coal Mining Industry

Coal mining is the methodology applied to extract coal from the ground. Coal mining methods have improved incredibly over the years. The increasing demands for coal over the years have caused the extraction methodologies to adapt to sustain the ever-increasing demand. At first manual labour was the only resource for extraction, whereas today automation has become much more conspicuous in the industry.

The BP statistical Energy survey states, “At the end of 2009 South Africa had coal reserves of 30408 million tonnes”. (MBendi, 2013) South Africa’s major mining operations are located in the Secunda-Standerton, Ermelo and Witbank-Middelburg areas of Mpumalanga. These areas produce over 70% of the country’s sealable coal. Mining operations started in South Africa, in 1889, and the coalfields in the Highveld area are nearing depletion. (Angelov, 2011)

1.1.2 Mining Methods

There are several mining methods used in the coal mining industry. As indicated in the diagram below, mining methods consist of two main categories, namely underground and surface mining. This project focusses on the underground mining method, specifically on the bord and pillar methodology (indicated with green in the diagram). This is also the most popular underground coal mining method applied in South Africa’s coal collieries due to its inherent safety, low capital investment, and relatively low operating costs. (Angelov, 2011).

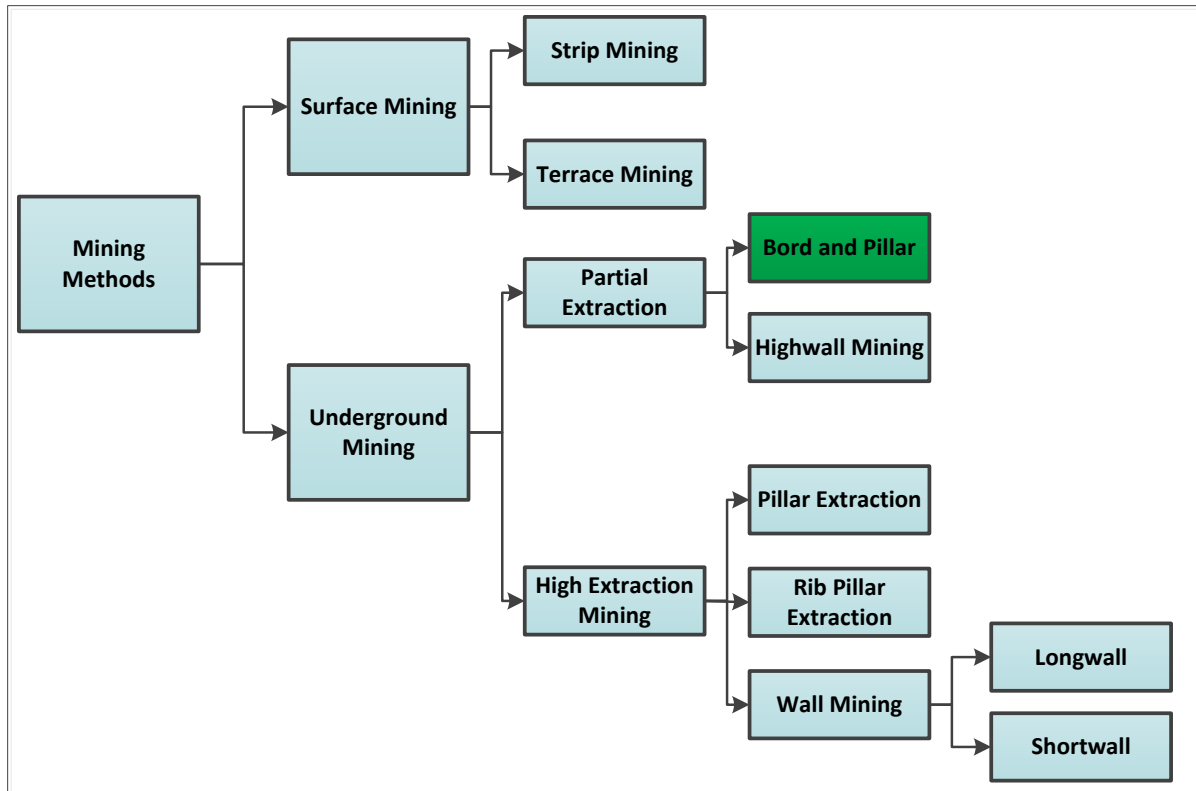


Figure 1: Mining Methods (Angelov, 2011)

The bord and pillar mining method is used in horizontal coal deposits in reasonably competent rock. The roof is primarily supported by pillars; this is the sections that are not extracted. The pillars' size is calculated with a specific safety factor provided by company policy. The coal is extracted in rectangular shaped bords from the coal seam. The continuous miners have nearly replaced all the conventional drill and blast sections. (Angelov, 2011) The diagram below illustrates the bord and pillar mining method by making use of the continuous miner and shuttle car to remove the coal from the mining face and conveyer belts to transport the coal to the surface.

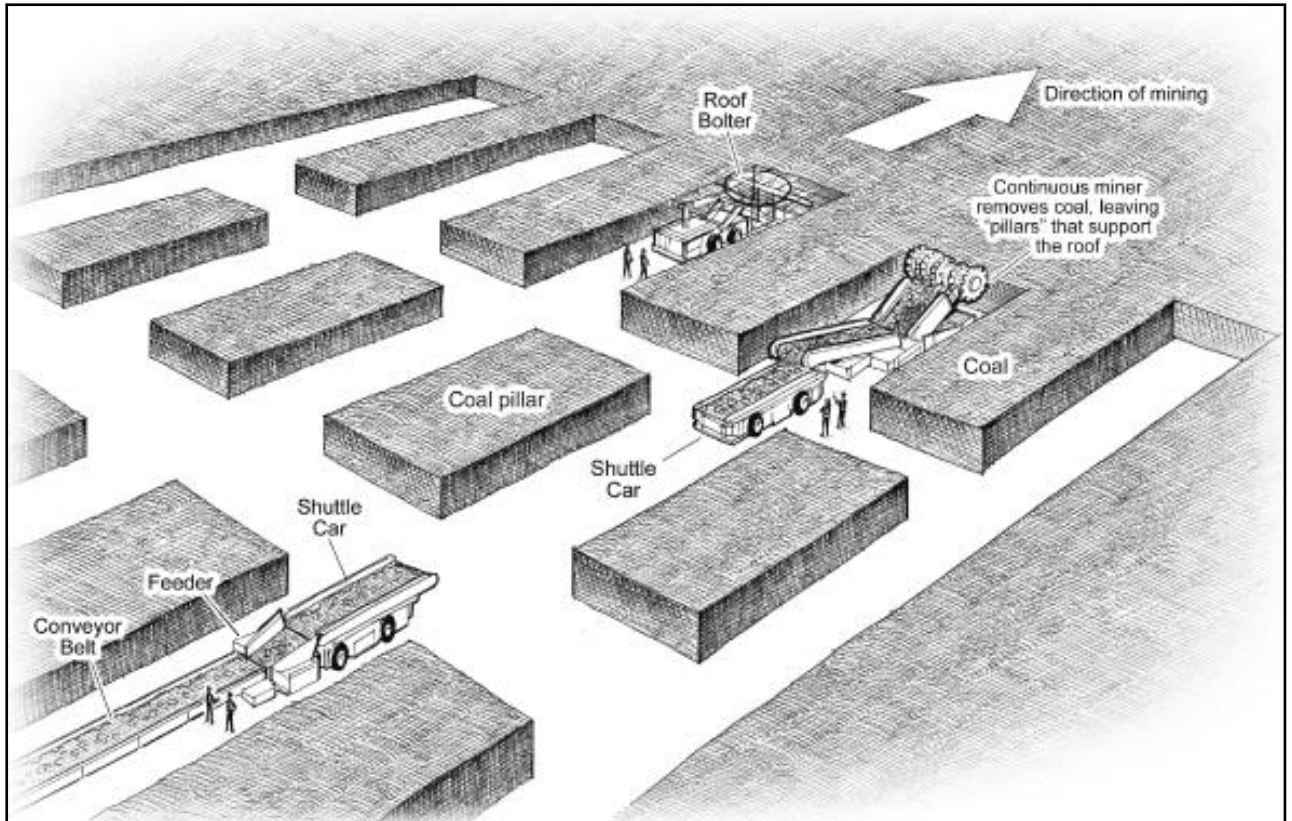


Figure 2: Bord and Pillar Mining Method (Anon., 2008)

1.2 Problem Statement

The challenge created by the dolerite is a variable that is addressed by the inclusion of the stoneworks process in the planning system of the mine. This section describes the relationship between the production section and the stoneworks team, the impact of an unforeseen dyke and the geological exploration analysis.

As ABC colliery reaches depletion and the available coal reserves become limited, the flexibility of operations become more constrained. The production section is restricted in its continued coal extraction the moment it reaches a large amount of dolerite intrusion (dyke or sill) and burnt coal. This dolerite intrusion requires the intervention of a stoneworks team before any operational activities can continue. This specialised stoneworks team will be responsible for removing the dyke through blasting techniques whereafter the production section can continue with normal coal extraction. If possible the production section starts working on another area while the stoneworks team removes the dyke. The production section will come to a standstill if the dolerite is not removed within a short period of time by

the stoneworks team. The coordination of the production and stoneworks schedules is critical to prevent standstills, which will result in production losses.

Encountering an unforeseen dyke or sill has different risks. In such a case there are two possible consequences. The first is the safety impact factor. If there is burnt coal present, there is a possibility of a safety hazard. It is dangerous and not allowed to mine in such areas. This type of hazard can cause an explosion. The second impact factor is loss in time which means the loss of production volumes. The first aspect to consider at production loss is whether there might be space available for alternative mining if an unforeseen dyke is reached, also known as pit room. If a pit room is available an unplanned section move is required. In the case of no available pit room, the stoneworks team must remove the dyke immediately. The time required to remove the dyke depends on the thickness of the dyke. The risk of an unforeseen dyke can be minimised by drilling more vertical or horizontal bore holes in order to attain a more accurate position of the dolerite intrusions. This more perfect information results in a trade-off between higher costs and more accurate information that will significantly reduce the risks of the safety impact and production volumes.

The mines that normally struggle with the possibility of a stoneworks bottleneck are the operations in the South Western portions of the Highveld coal seams. The seams there are typically the No. 4 and No.2 seams, which are deep (140-220m) and relatively thin (3.5-4.5m). Dolerite intrusions are abundant and impossible to see from aeromagnetic surveys due to the overlying sills.

1.3 Project Aim and Approach

It is of the utmost importance that the mine delivers on its planned volumes. It is therefore critical to examine the impact of the stoneworks process on production volumes delivered. The aim of this project is to quantify the risk of an unforeseen dolerite intrusion (dyke or sill). The result of imperfect information is the uncertainty of an unforeseen dyke. The goal is therefore to capture the value of an unforeseen dyke in a presentable model and to analyse the sensitivity of the input variables towards the generated expected value of the model.

The two main objectives are to generate an amount for the risk of an unforeseen dyke and to quantify the impact of production losses due to an unforeseen dyke. This model will justify

the maximum cost required for drilling and the impact of unforeseen dykes on production volumes delivered. The diagram below depicts the aim of the project:

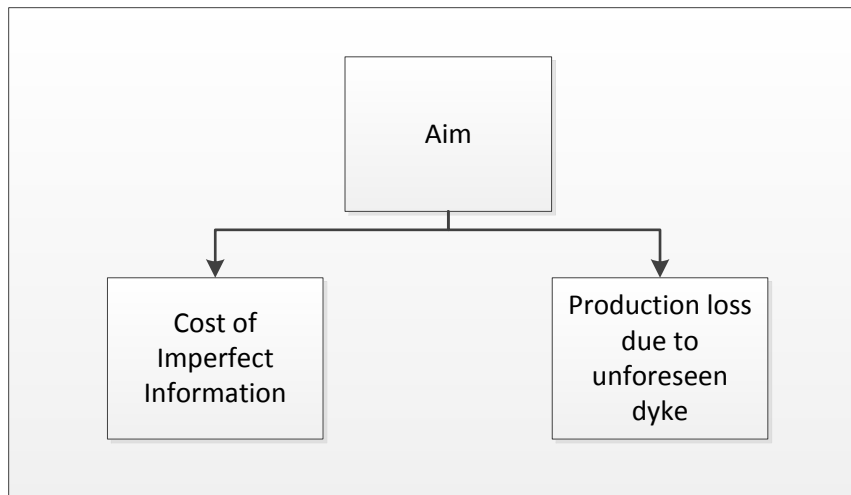


Figure 3: Project Aim

The project approach is divided into 4 stages, as indicated in the figure below.



Figure 4: Project Approach

1.4 Deliverables

The key *deliverables* of the project will be a report that will include the following:

- Literature research
 - A summary of the stoneworks process and the planning process of the mine.
 - Overview on operational performance and geological planning
 - Investigate the appropriate IE mechanisms
 - Selection of the best IE mechanism
- Data analysis and evaluation of geological coordinates
- Data analysis and evaluation of input variables of decision tree model
- Investigate alternative methods to quantify the problem statement
- Build a decision tree model to provide decision support
- Develop Monte Carlo simulation

- Develop sensitivity analysis
- Conclusions and recommendations

1.5 Rationale and Context for the Project Study

The motivation of the project is based on the results it can provide when the project is implemented. It is critical for the mine to deliver the amount of coal planned for. If the stoneworks process prevents the mine to provide this amount, it can have a catastrophic result. It is therefore critical to determine whether the stoneworks process is a bottleneck on the planned production volumes and what can be done to improve this situation.

Viewing the project as a system provides an unambiguous overview of the project and puts the project into context. A system can be divided into: suppliers, inputs, processes, outputs and customers (SIPOC). The diagram below indicates the three systems that are investigated during this study.

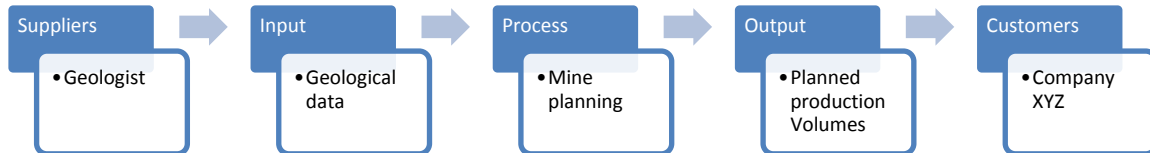


Figure 5: SIPOC of Mine Planning

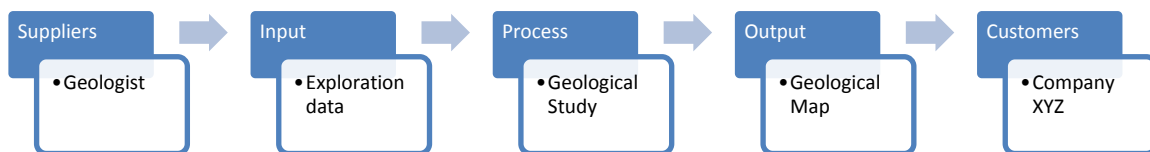


Figure 6: SIPOC of Geological Study

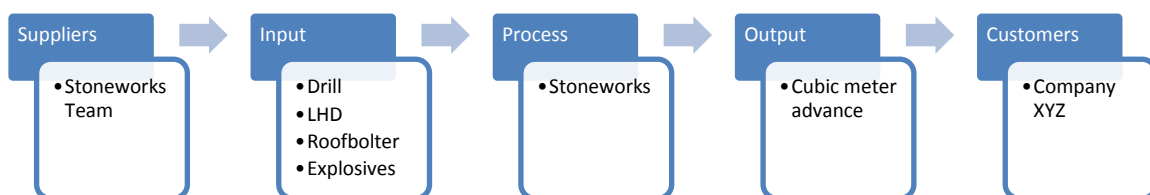


Figure 7: SIPOC Stoneworks Process

To grasp a better understanding of the project contextualization, one should plot the project on the mine value chain. The mine value chain starts at the exploration phase, and ends with end-user. It indicates the core value flow as well as the information flow. The diagram below illustrates the mine value chain and the position of this project on the mine value chain (red circles). This project performs in three major domains: geological exploration, mine planning and mining. The mining process in this project specifically refers to the stoneworks operations.

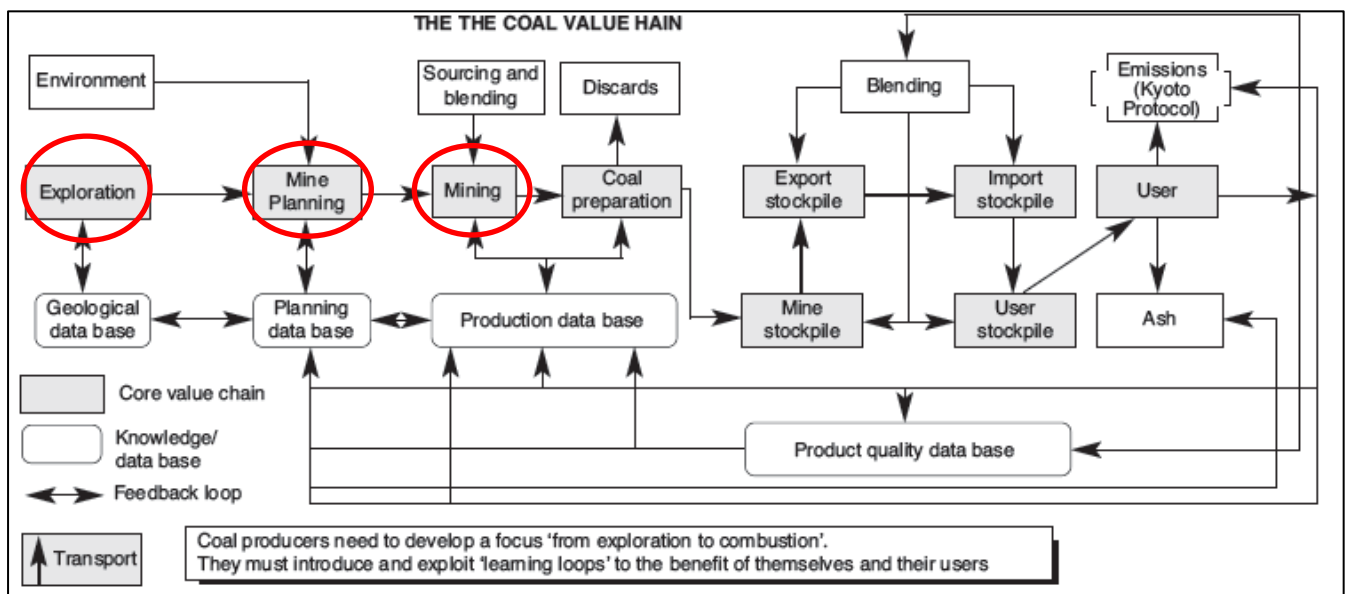


Figure 8: Coal Value Chain (Angelov & Naidoo, 2010)

Chapter 2: Literature Research on Mining Industry and IE Mechanisms

2.1 Introduction

This chapter consists of three sections namely: 2.1) the literature review, 2.2) the application of the literature review on ABC Colliery, and 2.3) Industrial Engineering mechanisms that will be necessary in analysing the problem in the project. The problem statement is impacted by three major processes namely: geological exploration, mine planning and stoneworks operations. It is necessary to investigate each of these processes to comprehend the impact they have on delivering planned production volumes. Each of these processes is discussed in the literature review as well as the application on ABC Colliery. The diagram below describes the layout of chapter 2.

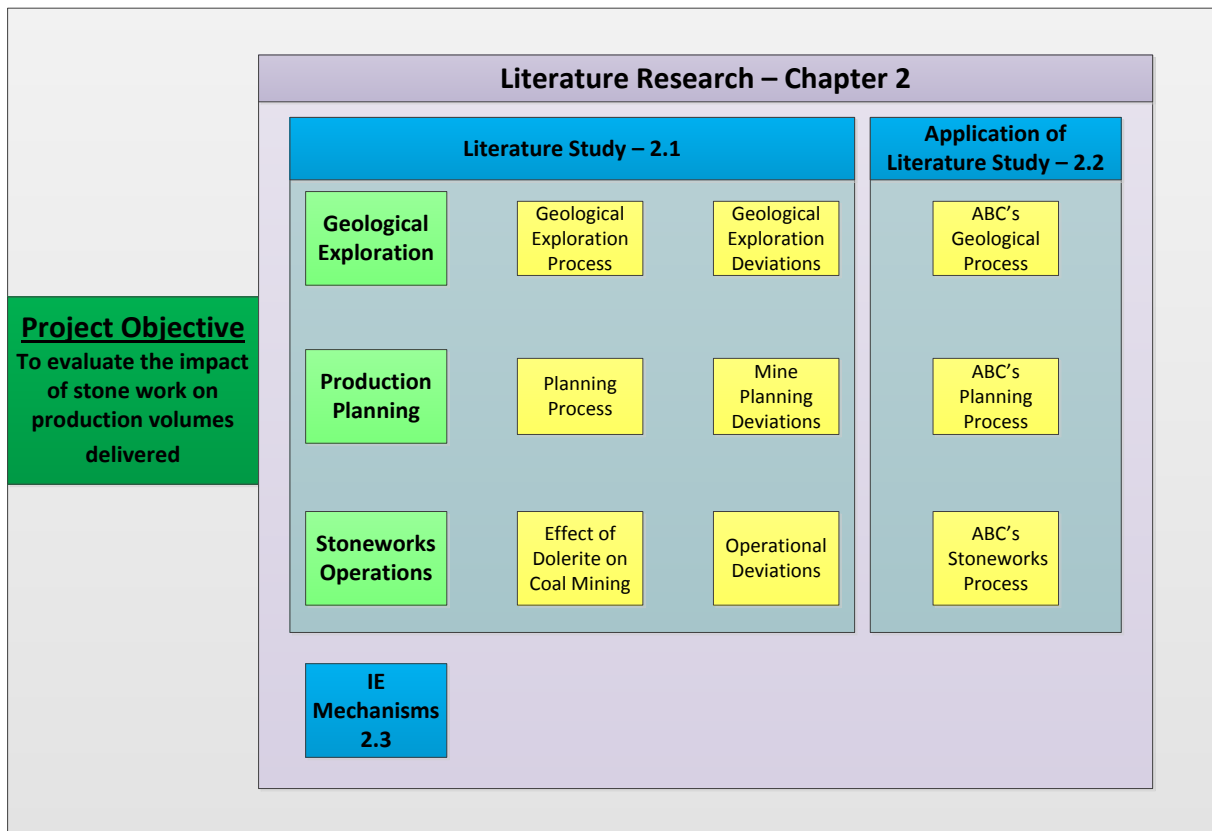


Figure 9: Chapter 2 Layout

2.2 Literature study

2.2.1 Geological Exploration

This section provides an overall understanding of the geological exploration process. To minimise the impact on mine planning, one should understand how critical it is to have accurate geological data to compile a mine plan. The geological study is divided into three categories. These categories include 2.2.1.1) exploration, 2.2.1.2) deposit assessment, and 2.2.1.3) geological errors.

2.2.1.1 Exploration

The geological process starts with the exploration phase. The purpose of coal exploration is to reveal the nature, location, and extent of the resources available in a certain situation. (Kung, n.d., p. 2) The two main objectives of a geological schedule are to determine the quantity and quality of the coal so that the mine is economically viable. There are a number of steps involved in a geological exploration. These steps are as follows:

- i. Legal title to explore the area
- ii. Evaluate the geological information
- iii. Develop surface explorations
- iv. Collect and analyse samples
- v. Predict the feasibility of the core body

The first step to the exploration is to compile a literature survey. The goal of the literature survey is to gather all the existing information on the remote area, thereby determining what data is still outstanding. From this survey, the geological framework as well as the topography should be assessed. The second step is to compile the map. During this step the data must be plotted onto a base map. The geological map describes the mineral deposit's size, shape, grade continuity, and variability. (Erickson, et al., 2011, p. 145) This map can also be used to indicate the igneous intrusions (dykes), faults, and other factors causing interruptions in the coal seam. (Kung, n.d.)

Geophysics play a critical role in the ore body investigation. The various methods include: gravity methods, magnetic methods, electrical resistivity, electromagnetic methods, seismic

reflection, and drilling for coal. Combined with the mapping of the field and the data from these methods, an appropriate plan can be drawn up for drilling to test the value of the reserves. (Kung, n.d.)

2.2.1.2 Deposit Assessment

The exploration geology is the discovery of potential valuable deposits which may develop into a mine. Project geology is the process followed after the determination of the specifications of the coal ore body and might include a feasibility study. This process then evolves into mining geology.

There are various factors influencing the mining geology. One of these factors is the characterization of the ore reserves. For a mining company to extract the resource effectively, it is essential for the company to have accurate characterization of resource-zone geometry. This accurate characterization requires precise geological databases during the geological phase. (Erickson, et al., 2011)

The success of the mining project is directly proportional to the accuracy and comprehensiveness of the geological database and the quality and comprehension of the description of the mineral deposit. It is the responsibility of the geologist to provide management with correct information. (Erickson, et al., 2011)

The importance of quality generates the opportunity to investigate the role of accuracy. The subsequent section deals with the need to improve accuracy and basic geologic data.

The accuracy requirement implies that a quality assurance system is in place. This system must ensure that the data is correctly entered into the system and that the data is accurate. It must be able to perform an automatic backup. The practice of geology is not easy and requires a great set of skills to interpret this data, obtained from exploration, correctly. (Erickson, et al., 2011)

To compile a geological map a number of categories are required. The categories include location information and data on mineralogy, samples, lithology, structural and rock properties. (Erickson, et al., 2011)

2.2.1.3 Geological Errors

There are three main types of geological errors namely: dykes, sills and displacements. The following paragraphs discuss their differences.

2.2.1.3.1 Dykes and Sills

Dykes are defined as igneous material that has moved into and through a seam forming a wall of rock, often burning or cindering the coal close to it. (Anon., n.d.). To extract the coal from this specific scenario, one has to go through the hard rock. The main difference between a sill and dyke is that a sill causes displacements and a dyke is only an intrusion or disruption in the coal seam. The diagrams below illustrate the difference in their properties.

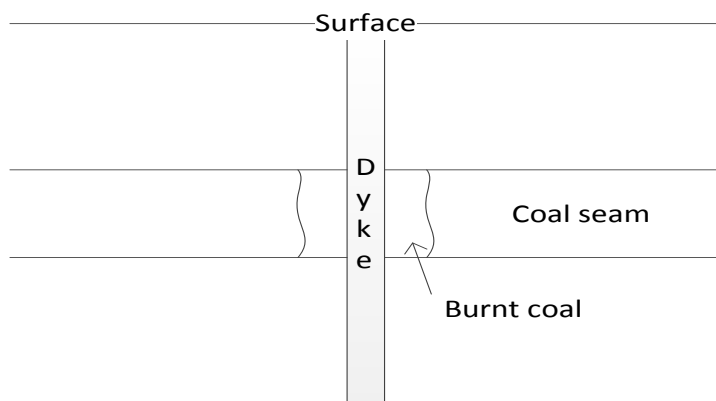


Figure 10: Dyke Side View

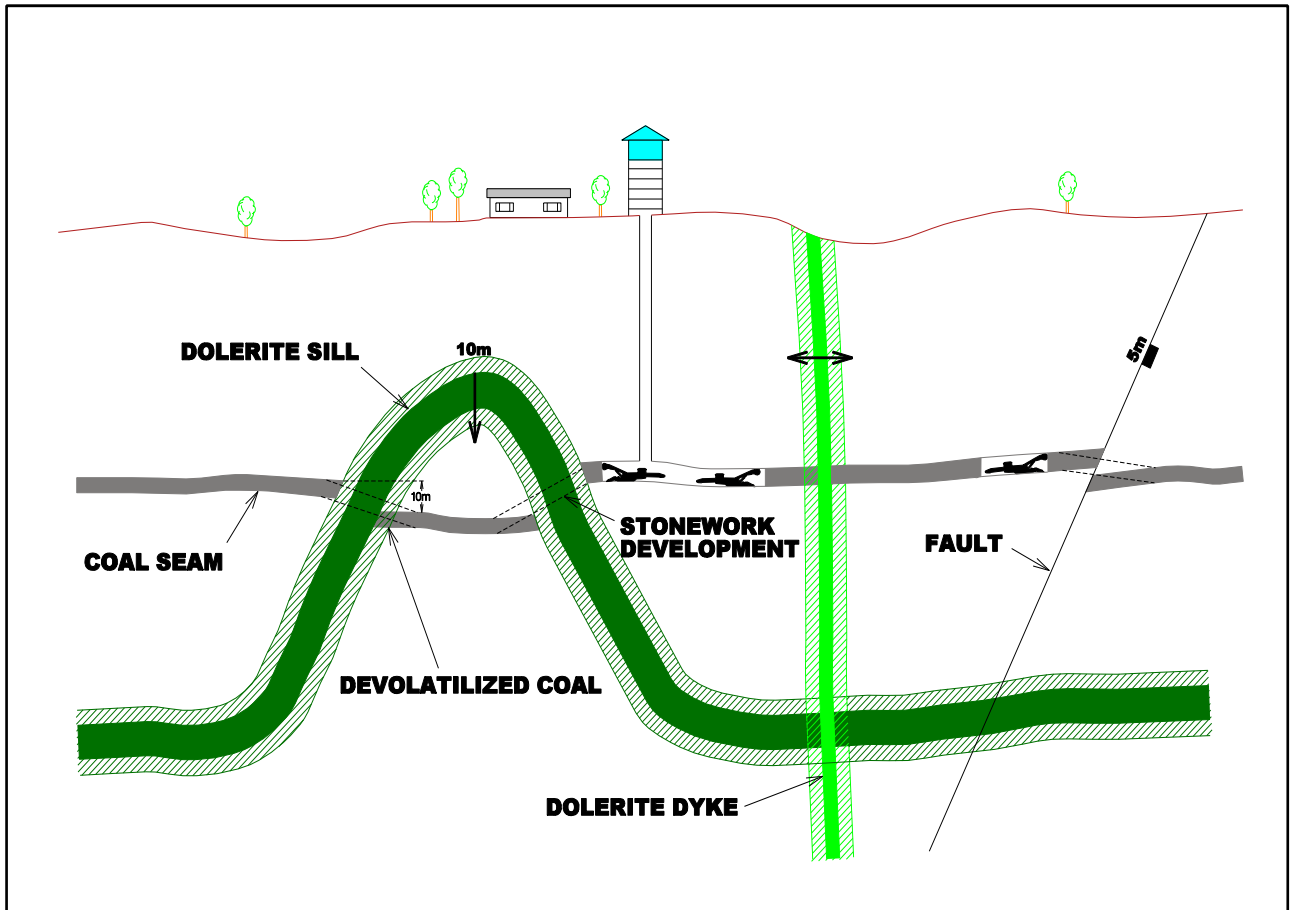


Figure 11: Dolerite Positioning (ABC Colliery Visitors' Presentation, 2013)

2.2.1.3.2 Faulting

2.2.1.3.2.1 Definition of Faulting

Nelson (1981) defines faults as “any break or fracture in the earth’s crust along which slippage has occurred”. Thus the strata have fractured and this is what causes the displacement of the earth’s crust on each side of the fracture. (Anon., n.d.) The slippage may vary in length and orientation. One that stretches over many kilometres could be barely noticeable and have minimal impact. The faults cause displacement of the rock layers, including the coal seam. (Nelson, 1981)

2.2.1.3.2.2 Types of Faults

There are different orientations of the faults. The first type is the normal dip-slip fault. The normal fault is caused by tensile forces acting on the rocks, therefore taking up more space. The one side moves downwards relative to the other side of the fault. The second, the reverse dip-slip fault, is caused by compression forces, therefore taking up less space. On the one side the rock moves upwards relative to the other side of the fault. The third type is transform (strike-slip) faults. This type is caused by a horizontal movement. As a result this type does not have an impact on the coal extraction process. Take note that diagrams are simplifications of the actual state. It may also be possible that a combination of the faults can occur. (NESTA, 2010) The diagrams below illustrate the three types of displacements:

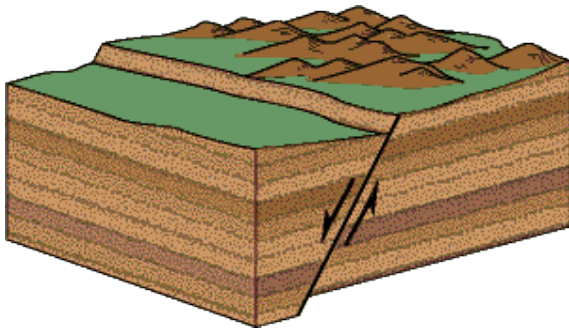


Figure 12: Normal Fault (NESTA, 2010)

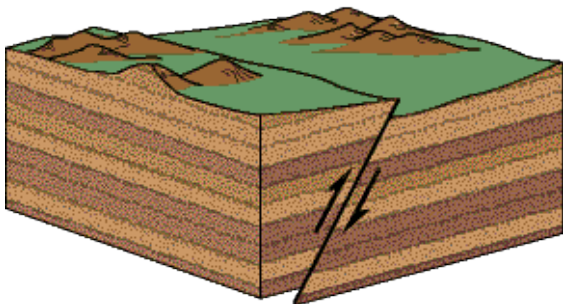


Figure 13: Reverse Fault (NESTA, 2010)

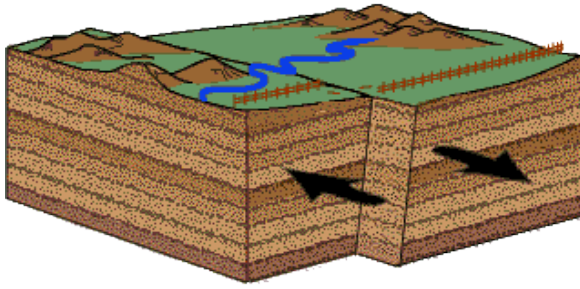


Figure 14: Transform Fault (NESTA, 2010)

2.2.1.3.2.3 Origin of Faults

Faults are divided into two main categories of origins: tectonic and nontectonic. Tectonic faults are formed by forces acting over large areas. The position can usually be forecasted in unmined areas. Nontectonic faults are formed when stresses affect sediments while it is being transformed into rock. These faults are more difficult to predict in unworked faces. (Nelson, 1981)

2.2.1.3.2.4 Effects of Faults on Coal Mining

There are various effects on coal mining. These effects include:

- Displacement of coal seams
- Weakening of roof in underground mines
- Influx of water and gas along faults
- Impurities in coal

Each of these effects is addressed in a different way. Most of these effects are taken into consideration when the mine is developed, especially the placement of the shaft. There are stages where these faults cannot be avoided.

2.2.1.4 Geological Exploration Deviations

There are numerous events that can cause the geological study not to develop as planned. Below are some of the possible problems that may occur during development (Angelov & Naidoo, 2010):

- Interpretation incorrect
- Exploration Data inadequate (XPAC)
- Changes in the mining environment:
 - Poor floor/roof conditions
 - Major geological discontinuities
 - Rain storms and flooding
- Incorrect Planning
- People uninformed:
 - Plan not communicated
 - Re-plan not communicated
 - Incorrect interpretation of plans
 - Ignorance of plan

2.2.2 Mine Planning Process

2.2.2.1 What is Underground Mine Planning?

The planning process is concerned with the physical exposure of the coal in given periods and at specific quantities and qualities. It is important to have a clear understanding of the risk associated with the specific location of tonnages and qualities. There are three levels of planning: life of the mine (LOM), long term plan (LTP), and short term plan (STP). These levels are interlinked and represent a different level of risk. (Angelov & Naidoo, 2010)

Underground mine planning is a fundamental subject in mining. The planning begins with resource detection and delivers a production schedule. Mine planning can be difficult; therefore it is divided into several phases. (Meunier, Unknown) The goal of underground mining is to achieve the optimal layout of the underground workings that deliver the most of the ore body at the lowest cost, and with maximum safety. (Hem, 2012)

The subsequent paragraphs discuss the different levels of mine planning.

2.2.2.2 Life Cycle of a Mine (LOM)

Mine planning is only effective and efficient if it is done for the life cycle of the process, project or organisation. In the life of a mine plan the coal reserve is defined together with required infrastructure and costs. (Angelov & Naidoo, 2010) The life cycle steps for a mine are indicated in the figure and are elaborated in the following section.

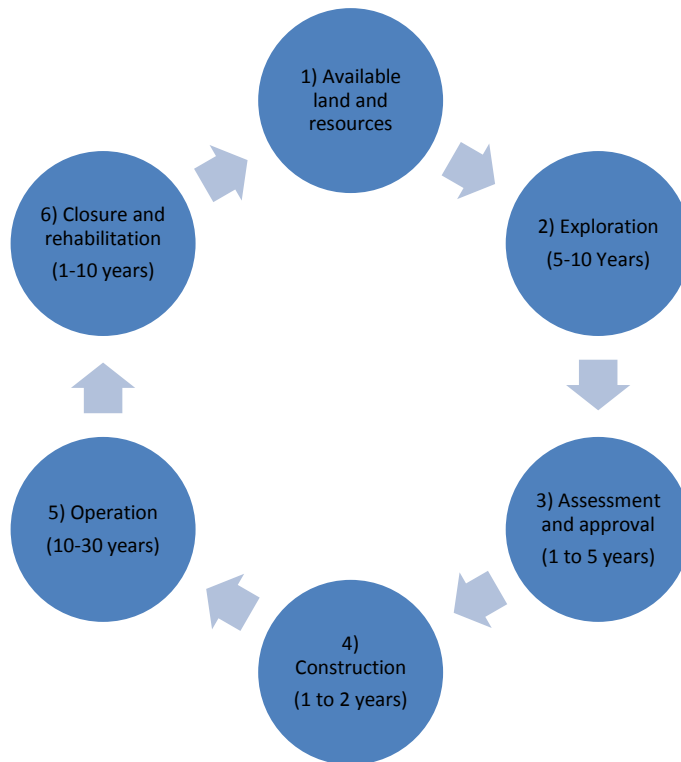


Figure 15: Life Cycle of a Mine

- Available land and resources

The cycle is initiated by determining the resources and land available for mining. It is critical to have access to as much land as possible to improve the likelihood of finding the minerals. Mineral deposits that are valuable and abundant are rare to find. (Columbia, n.d.)

- Exploration (5 to 10 years)

Exploration is the search and examination of mineral deposits. It is the official first step of the mine cycle. In early stages of exploration large areas are surveyed by geologists and prospectors. The data collected from the survey is mapped. Certain areas are singled out for more detailed studies, based on the map and existing data. If the area singled out is valuable enough for development, it is claimed via an online application system. The second step of the exploration phase is an in depth study of the ore body. This includes horizontal

and vertical drilling. During this phase data collection for the environmental studies begins. (Columbia, n.d.)

- Assessment and approval (1 to 5 years)

The information gained on the ore body and the environment is used to plan and design the mine. This planning includes determining whether mineral extraction is possible within economical and responsible boundaries and with a minimal environmental impact. The mine must provide social and economic benefits to the communities and province. The ore body must be rich enough in minerals to justify the capital requirements for mining operations and closures. During this phase it is the duty of the mine developers to address the needs and requirements of the community and government agencies. It takes approximately two years for data collection on the environment and the feasibility of the mine and another one to two years for environmental assessment and permitting. (Columbia, n.d.)

- Construction (1 to 2 years)

This phase includes the construction of the mine, required buildings and necessary infrastructure. The duration of this phase depends on the remoteness of the area, the complexity of the development and the effort necessary for the regulation and review of the processes. (Columbia, n.d.)

- Operation (10 to 30 years)

Well trained personnel are required for the operation of the mine. As a result hiring, recruitment and intense training are necessary. The production of the mine includes extraction of the ore body according to the best suitable method, waste disposal and shipment of the extracted minerals. Continuous exploration is part of this phase for future mine development. (Columbia, n.d.)

- Closure and rehabilitation (1 to 10 years)

The last phase of the mine's cycle is the mine closure. It includes removing equipment and facilities and the safe closure of mine processes. The goal of the closure phase is to provide a sustainable ecosystem for all fauna and flora. (Columbia, n.d.)

2.2.2.3 Requirements for Underground Mine Planning

Firstly, information is needed from several resources to obtain an underground mine plan. This consists of geological, structural and mineralogical information combined with data on the reserves and resources. The selection of the potential mining method and sizing of the mine production is based on the information collected. To complete the mine plan, the development planning is done, mine manning and equipment are selected, all leading to

examination of the foregoing mine plan. One cannot assume that the above mentioned sequence will guarantee an efficient and effective operating mine. It is important to realise that it will only be the best mine operation if it is the best possible mine plan, done correctly. Deviation from the best possible mine plan may lead to an unwanted mine operation. Mine planning is an ongoing process that requires continuously determining the optimum plan. The subsequent section discusses the various requirements for an underground mine plan. (Hustrulid & Bullock, 2001)

2.2.2.3.1 Geotechnical and Physical Information Required

i. Technical Info needed for preliminary mine planning:

The technical information needed is gathered during the exploration phase of the mine development cycle. The information includes:

- Access and location of the land to be mined
- Description of the surface topography
- Description of local, regional, and mineral deposit geology
- Re-evaluation of exploration activities
- Tabulation of potential resources and ore reserves
- Description of the ore body calculation method
- Definition of the company's property position
- Description of the company's position of the water
- A Metallurgical and geotechnical study
- Social and environmental issues

There is a possibility that more information will be required on these subjects at a later stage. Gathering information during the exploration phase will save much time during the feasibility and development phase. (Hustrulid & Bullock, 2001)

ii. Mineralogical and geological information

Overall comprehension of existing structures and similar rock types in the mining district will benefit the mining plan. A new mine has a greater risk of making costing errors during the development phase than mines that are developed later. The information required includes:

- Full description of the size (length, width and thickness) of the ore body
- The depth of the coal seam
- Interruptions in the coal seam
- Variation in the quality grades of the economically viable coal seam considered

- Distribution of toxic minerals
 - Quality and quantity of the ore reserves and resources with detailed cross sections (Hustrulid & Bullock, 2001)
- iii. Structural information
- The structural information needed includes the following:
- Overburden depth
 - Detailed description of overburden, including:
 - Type
 - Structural features in relation to proposed mine development
 - Structural features with regard to the mineralized zone
 - Information about water, oil, or gas that might have been found
 - Structure and quality of the host rock
 - Structure of the mineralized material (Knobbs, 2012)
- iv. Property Information
- The information needed on the property includes:
- Details of land and surface ownership
 - Availability of water
 - Positioning of mine in relation to any existing railroads, roads, rivers, power and community infrastructure
 - Regional, local and national political situations (Knobbs, 2012)

2.2.2.4 Stages in Underground Mine Planning

The process of mine planning consists of five stages. The first step is the feasibility stage. During this phase attention is given to techno economic limits of extracting the minerals from the ore body. The second phase is the design optimisation. After confirming that the mine is feasible, an optimal design is created to access the ore body. The third phase is to develop scheduling. This stage involves scheduling the design on a short and long term basis. The scheduling can be done by a manual approach or with analytical computer techniques. The fourth stage is concerned with production scheduling. During this stage the goal is to implement the schedule in the ore body. The objective of production scheduling is to maximize the return on investment and the net present value that can be derived from the extraction and sale of the ore body. The production scheduling can be categorised in two steps, namely: the mining sequence, and deciding on an optimum production rate. The last step includes further exploration. This means that planning is an on-going, continuous process. This stage ensures the economic viability of the mine. (Hem, 2012)

2.2.2.5 Factors Considered for Mine Planning

Mine planning is a challenging task because of certain complexities involved. The following are potential factors which may impact the mine planning (Hem, 2012):

- Complications due to the mining method selected
- Geotechnical rock assessment
- Location positioning of the mine
- Availability of mine services
- Scheduling constraints
- Production capacity
- Safety issues

2.2.2.6 Types of Underground Mine Plans

There are two main categories of mine plans. The first type is a short term mine plan. This category exists of a three month plan which is updated every month. The daily and weekly plans are derived from this plan. The second type is a long term mine plan. This category exists of a one year plan, a three year plan and a ten year plan. This category is only updated at the end of each financial year. (Hem, 2012) Angelov and Naidoo (2010) provided the major objectives of the sort term plan, which include the following:

- Grade control
- Cost control
- Equipment utilisation
- Labour productivity
- Capital productivity

2.2.2.7 Underground Mine Planning of Specific Activities

Specific activities are necessary to complete an efficient and effective mine plan. The following activities must be built into the mine plan: mineable reserves, production capacity, mining method, mine design, mine transport, ventilation, mine services, manpower, surface facilities, capital costs, operating costs, production and economic model and finally risk assessment. (Hem, 2012)

Mine planning depends on a number of parameters. Each of the parameters contains a degree of uncertainty, which incorporates a level of risk within the mine planning process. The risks can be eliminated by improving information. Angelov and Naidoo (2010) defined these parameters as follows:

- Mining method selection
- Geological and geotechnical data
- Equipment and degree of mechanization
- Efficiency of processing plant
- Economics

2.2.2.8 Common Underground Mine Planning Problems

- i. A problem can occur if there is variation in the terminology used. As an example the literature refers to production rate per shift. Often, it is not stated what the length of the shift is. This can cause confusion in consistency of the plan.
- ii. It is of the utmost importance that the information used and the assumption made to compile the plan is correct. As it is a new mine there is no previous information to support the current findings. As a result it will be necessary to continuously refine and adjust the mine plan to adapt to any new findings.
- iii. A problem may occur during the handover from the planning phase to the implementation phase. Different people are responsible for the different phases. As a result some information may be lost during the handover. (Anon., n.d.)
- iv. Planning deviations that might occur:
 - a. Incorrect Standard Times
 - b. Incorrect scheduling - overlapping of resources
 - c. Incorrect interpretation of geological information
 - d. Activity not allowed in the plan
- v. A problem will occur if the geologist does not do regular underground visits.
- vi. The mine planner and the geological section must communicate on a regular basis. If the communication is not sufficient, the mining processes will not align with the mining activities.
- vii. A problem can be caused by insufficient horizontal drilling information on which to base the mine plan or if the information is incorrect.

2.2.3 Handling of Geological Faults in Coal Mining

2.2.3.1 Introduction

All mines address their geological errors differently. Each of these effects will have a different impact on the mine. Previous research has been done on the effects of dolerite in the Witbank mine areas. This section will elaborate on the differences in impact of these errors.

2.2.3.2 The Effect of Dolerite on Coal Mining

The list developed is based on the effects that dolerite (sills and dykes) has on the coal mining environment. The effects include:

- i. Sill can have a thermal effect on the coal. This can cause devolatilised coal.
- ii. In general the thermal effect of dolerite sills intruding on coal seam has a greater impact than the dolerite dykes have.
- iii. The devolatilised coal has the tendency to become brittle during and after mining resulting in fine coal. This can result in pollution.
- iv. More geological errors lead to unfavourable mining conditions. As a result an increase in roof support is necessary, which leads to extra costs. The working conditions may be unhealthy and unsafe.
- v. Due to the burnt coal, higher methane concentrations may occur. This can increase the possibility of methane and coal dust explosions.
- vi. The sills influence the floor and roof stability, which leads to poor mining conditions. This increases the roof support cost and poses a higher safety risk.
- vii. The floor stability decreases in the areas and is caused by the thermal effect of dolerite.
- viii. The groundwater is influenced by the sills and dykes.

(Du Plessis, 2008)

2.2.3.3 Operational Deviations

There are several deviations which may prevent the stoneworks process to perform as planned. Listed below are some of these deviations:

- Drilling
 - Drill bits not complying with specifications
 - Maintenance not up to date
 - The lack of cable handling
- Charging
 - Not a sufficient amount of explosives in the face, or a shortfall in availability of explosives.
- Blasting
 - Explosives not properly connected
 - Rock size inadequate - second break is thus required
- Loading
 - Maintenance on LHD not up to date
 - Diesel requirements
- Roof Support
 - Shortfall in availability of material in the face
 - Maintenance - cable handling and single boom Fletcher
- Priority Change
- Logistical support
- Interruption of work due to the presence of methane gas

2.3 Application of Literature Study on ABC Colliery

2.3.1 Introduction

In this chapter the knowledge gained during the literature study is applied specifically to ABC Colliery. An in depth study is compiled on different applicable processes. The process that was investigated, includes the geological exploration process, the mine planning methodology and the stoneworks process.

2.3.2 ABC Colliery's Geological Exploration and Data

The geological process consists of various consecutive steps. The steps are elaborated in the following paragraphs.

The initial phase of mine development is the exploration phase. During this phase a block of land is obtained for exploration. The time required to complete this study is approximately 5 to 20 years. It includes prospecting and getting the mining rights approved by the DMR. Part of this phase is to determine the borehole density. The last step of this phase is the scheduling of the section deployment (when does the mine plan on moving in). The resources required for the exploration phase include drilling contractors for directional and vertical drilling, a laboratory to analyse the coal samples, an experienced exploration geologist to log the core, geophysical logs to verify data from the directional drilling, vehicles capable of functioning on the specific terrain, and the permission of farmers to enter their property.

The second step in the process is the mining of the area. The time required for this phase can be anything between 2 to 4 years for the first section to be deployed. The shafts and declines need to be sunk once a suitable area has been found through the exploration phase. The resources required for the phase include geological model information to select the best place to sink the shaft and schedule the area for mining, mapping of the shafts, additional drilling information for effective support strategies, contractors to sink the shaft, qualified personnel to do the scheduling, project managers, cost controllers and enough employees - from the mine manager to the general worker underground.

The stoneworks are an extension of the geological process. The time required for a geological study is between 1 to 6 weeks depending on the geological structures. The resources required include roof, floor and seam information, the coal quality information and correct thickness and locality of the structures.

This paragraph provides the flow of mapping for the geological process. Before the mining planning can begin, certain steps need to be followed. Vertical drilling is the first step. Before the mine can open at least 1 borehole per 25ha is required. The results of the boreholes are plotted, forming a model of the boreholes. From the borehole model a geological map is created which captures the data on the mining height and inorganics. The last step is to create the mining layout.

2.3.3 ABC Colliery's Mine Planning

The methodology of planning evolved over the years at ABC Colliery. The capacity needed for planning was originally determined by Company XYZ. This was only a one-sided methodology with minimal consideration of the actual mine capacity. It was calculated what the need will be for coal during the upcoming year, then that amount was divided between the five collieries. Each mine was then responsible to plan each month's deliverable to meet the requirements from Company XYZ. This methodology has failed in the past because the mine has not been able to meet requirements due to the availability of the coal reserves.

Today the methodology has been adapted to take the mining capacity into consideration. The planning phase starts with a long-term plan (budget) for the financial year. Based on the geological map, it is then determined when it will be necessary to mine certain areas.

The first step for short term planning is to determine the capacity for each month that the mine is able to deliver in its specific condition. A planning calculator was built to determine this capacity. The information needed as input to the calculator is received from the geological maps. The following section discusses each of these inputs.

The main factor that influences the capacity is the coal seam height, also known as mining height. The seam height is directly proportional to the mine capacity. Other factors influencing the capacity are the hardness of the inorganics in the coal seam, the capacity of the shuttle car, the size of the cutter head, the size of the centres, geological influence and the number of section moves required. The calculator determines whether the factor has a positive or negative impact. The harder the inorganics in the coal seam are, the longer it will take to extract the coal and as a result productivity will decrease. The inorganics can range from 0 to 500mm. The productivity will increase if the capacity of the shuttle car (vehicle to transport coal from continuous miner to conveyer belt) increases. The selection of shuttle cars consists of 16 tons, 10 tons and 20 tons. ABC Colliery standardized with 16 tons shuttle cars. The different cutter heads can increase productivity. There are two types of cutter heads namely standard and mega. The mega cutter head can increase productivity with up to 3%. ABC Colliery uses the bord and pillar coal extraction methodology. An integral part of the planning is to determine the size required for the pillars so that it meets the safety requirements. This safety factor calculation is based on the overburden depth. As the size of the pillar increases, the productivity decreases due to enforced mining sequence (the pattern used to mine for optimal ventilation). The geological structures reduce productivity. These

structures include dykes, bad roof and soft floor. If it is required to move a section, it will decrease the productivity, depending on the distance that needs to be travelled.

The diagram below illustrates the mining height of ABC Colliery. This is also the first geological map required to determine the mine's capacity.

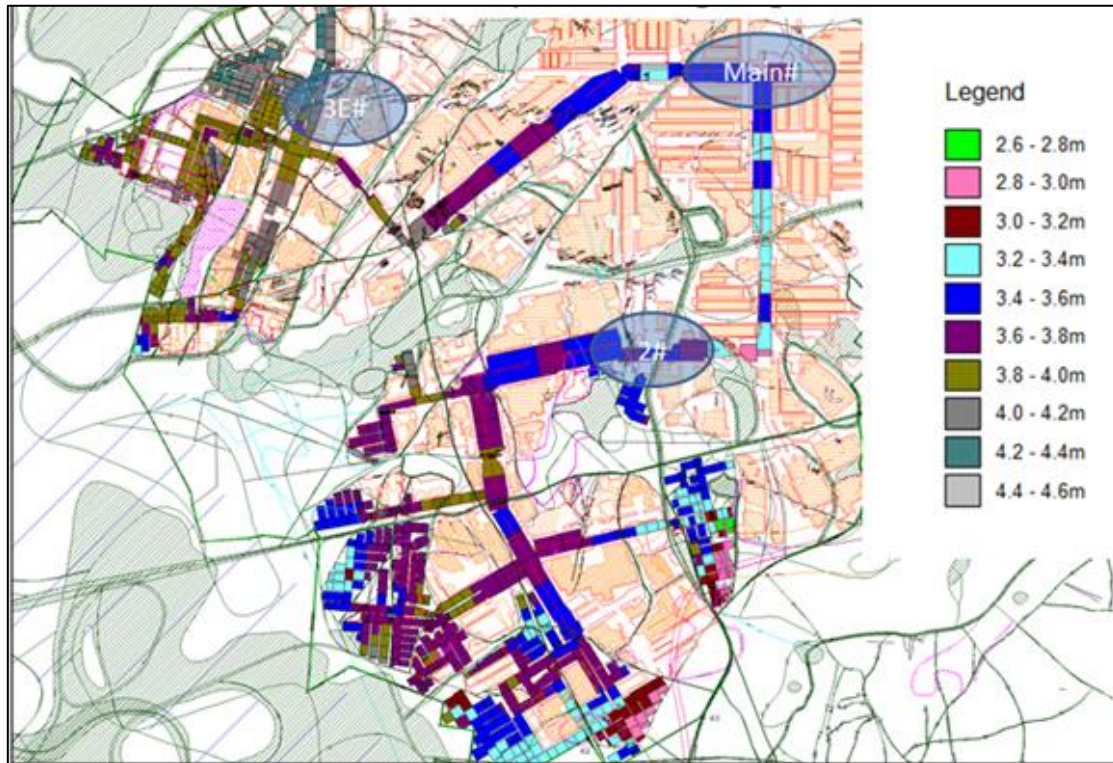


Figure 16: Mining Height

The diagram below indicates a geological plan of the inorganics present in the coal seam.

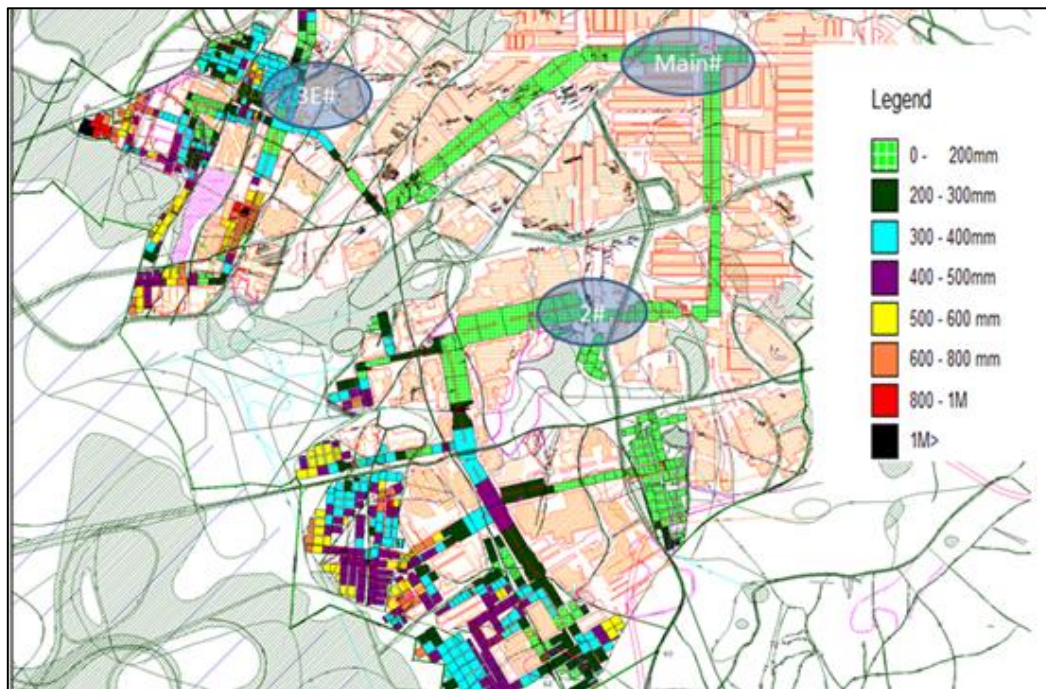


Figure 17: Inorganics of ABC Colliery

The diagram below is the geological map of the overburden of ABC Colliery, which has an influence on the safety factor.

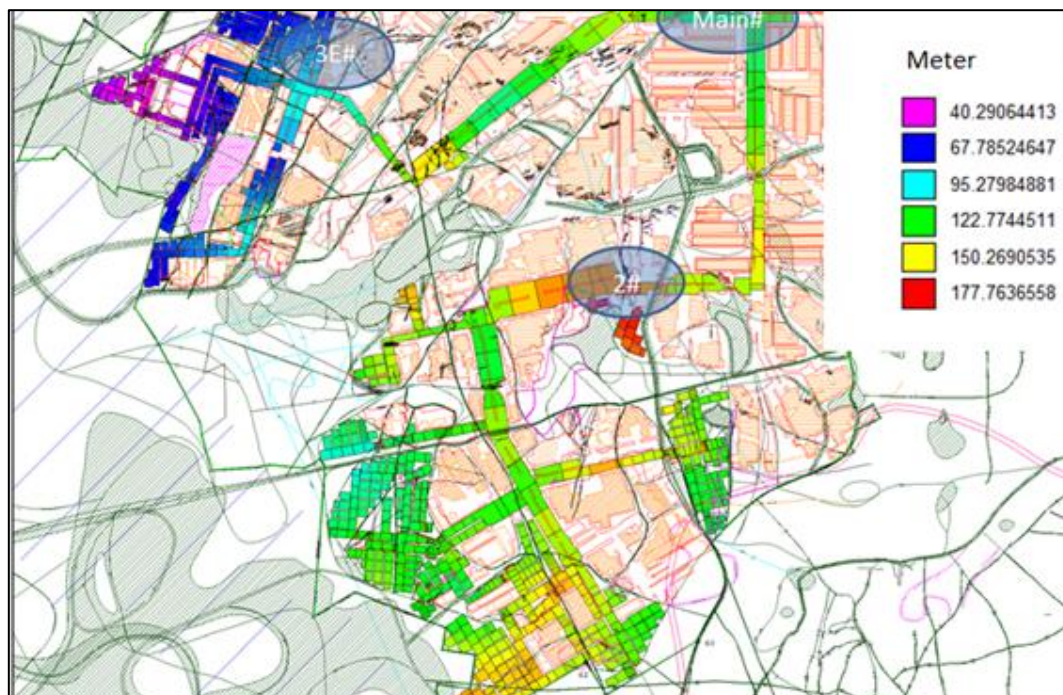


Figure 18: Overburden Depth of ABC Colliery

The diagram below is a typical representation of a long-term mine plan. This plan is for the financial year 2013 until 2019.



Figure 19: ABC Colliery Budget Years

2.3.4 Stoneworks Process at ABC Colliery

One of the challenges that underground coal mining faces is addressing the presence of dolerite in the coal seam. Dolerite is a very hard rock, which is caused by volcanic activity. There are two types of dolerite, namely horizontal dolerite also known as sills and vertical dolerite also known as dykes. Both sills and dykes can cause interruption in the mining operations (Collings, 2002). In cases as stated above, a specialist team will be required to remove the dolerite. These teams are called stoneworks teams.

The stoneworks process consists of five sequential steps as indicated in the diagram below. The first step is to drill the required amount of holes into the face. The resources required for the drilling process are a face drill, an operator and a cable handler. Secondly, each hole that was drilled in the previous step, is charged with explosives. After the face is blasted, the rock and rubble is removed from the blasted face by loading it onto the Load Haul Dump (LHD) and dumping it at the stowing area. The last step of the process is to support the roof with a single-boom Fletcher.

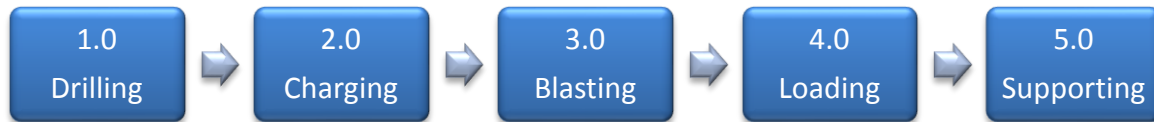


Figure 11: Stoneworks Process

2.3.4.1 Problems Occurring at Other Mines

As part of the investigation it was noted that all the mines with a horizontal ore body encountered the same problem, i.e. that the stoneworks process became a bottleneck. The reason was that the coal extraction equipment could not mine through geological errors. As a result a specialised team was required. As a mine nears the end of its life, coal reserves become scarce, forcing the mine to consider areas previously thought to be too difficult to mine. (Angelov & Naidoo, 2010). Mines with more available reserves have the luxury of obtaining coal from another section if the stoneworks become a bottleneck, to uphold the required demand. As the mine's life comes to an end, less available reserves for mining are encountered. The option to move to another section is not always a possibility. As a result it becomes more critical to determine whether stoneworks will become a bottleneck.

An integral part of this section is to gather information with regard to the similarity of this problem at other mines. The data was acquired at one of South Africa's top mines. The mine's only operating underground mine has a relatively "clean" coal seam, with the odd stringer of dolerite intrusion or dyke of less than one meter, but seldom thicker than three meter. When a section was interrupted by a geological feature, a blast crew was sent to deal with the removal of the dolerite material. The area would require additional resources and continuing with the activities in the area would be determined by the availability of ground to mine, while the drill and blast team went through the dolerite intrusion.

In conclusion there are definitely other mines that manage the same type of problem. Dykes and stringers of less than two meters are nearly impossible to detect with exploration boreholes. It is typically these intrusions that are not on the plan, and would not have been accounted for in the design of the mine plan.

The stoneworks process is a bottleneck if mining is interrupted due to either the availability of a coal seam or the rerouting of the front of mining. It often occurs that the front of mining is

rerouted or even worse, that the mine activity is temporarily stopped due to the unavailability of the coal seam for mining. Therefore stoneworks are a bottleneck in the mining of coal.

2.4 Industrial Engineering Mechanisms

2.4.1 Introduction

The purpose of this section is to investigate alternative Industrial Engineering methods that can be used to analyse the problem. The investigation includes the purpose of the method, methodology applied, applicability in the mining industry and the results of the usage. In the scope of this project various methods are applicable. The methods that will be discussed include: decision analysis, risk analysis, sensitivity analysis, Monte Carlo simulation and value of information. The last part of this section discusses the applicability to the current ABC Colliery stoneworks investigation.

2.4.2 Decision Analysis

The main purpose of decision analysis is to enable the decision maker to make better decisions in complex situations, usually where uncertainties are involved. The quality of the decision is based on the expected consequences (impact) and the stated preferences of the decision makers. The analytical framework assists the decision maker to think in a systematic manner about the objectives, preferences, uncertainty and structure of the problem. The decision analysis results in a model that quantifies the decision. (Covaliu, 2001)

If there is an uncertainty involved with regard to a required outcome, certain decisions have to be made. To make such a decision is rarely easy. The application of decision analysis techniques can lead to better decisions with improved outcomes. (Robert T. Clemen, 2001)

The process flowchart of the decision analysis is shown in figure 11. The first step is to identify the decision, understand the objectives of the decision, to identify what is important. If the objectives are clear, the alternatives can be identified. The next step is to decompose and model the problem. At this stage it is important to distinguish between modelling

decisions, modelling uncertainty and modelling preferences. The flow chart is used to choose the best alternative. To prove that the best result was chosen, sensitivity analysis is performed. If the sensitivity analysis indicates that further analysis is required, steps 1 to 3 must be repeated. (Robert T. Clemen, 2001)

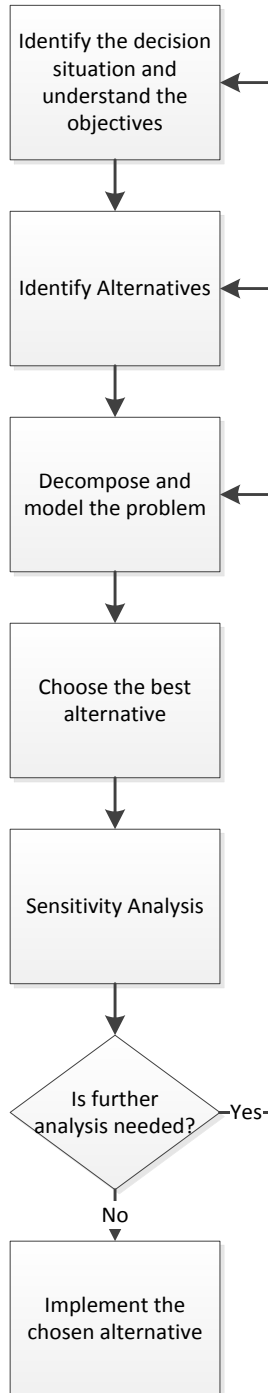


Figure 11: Process of Decision Analysis (Robert T. Clemen, 2001, p. 6)

According to Covaliu the main elements of a decision problem include the following (Covaliu, 2001):

- Decisions to be made by the decision maker
- Uncertainty events
- Consequences
- Objectives and preferences
-

The first step to model decision is to determine whether to maximize the profit or minimize the impact. In this case one wants to minimize the impact of the stoneworks process on the volumes produced. The decision can be modelled in two forms: influence diagrams and decision tree. (Palisade, 2010)

There are various methods that can be evaluated during a decision analysis. One of these methods includes a decision tree.

A decision tree is a complete tool for modelling a decision problem. It illustrates the problem in great detail. This tool makes use of chronological events to describe the decisions and their probabilities. The model is divided into two components: nodes and branches. There are three types of nodes: the chance node, the decision node, and the end node. The chance node is indicated with a square, the decision node with a circle and the end node with a triangle. The branches are used at each node type. It is used as follows (Palisade, 2010):

- Each possible outcome is connected to a branch at a chance node
- Each option is connected to a decision node
- The end node is not connected to any branches. It indicates the payoff and probability of the specific path

The diagram below depicts an example of a decision tree.

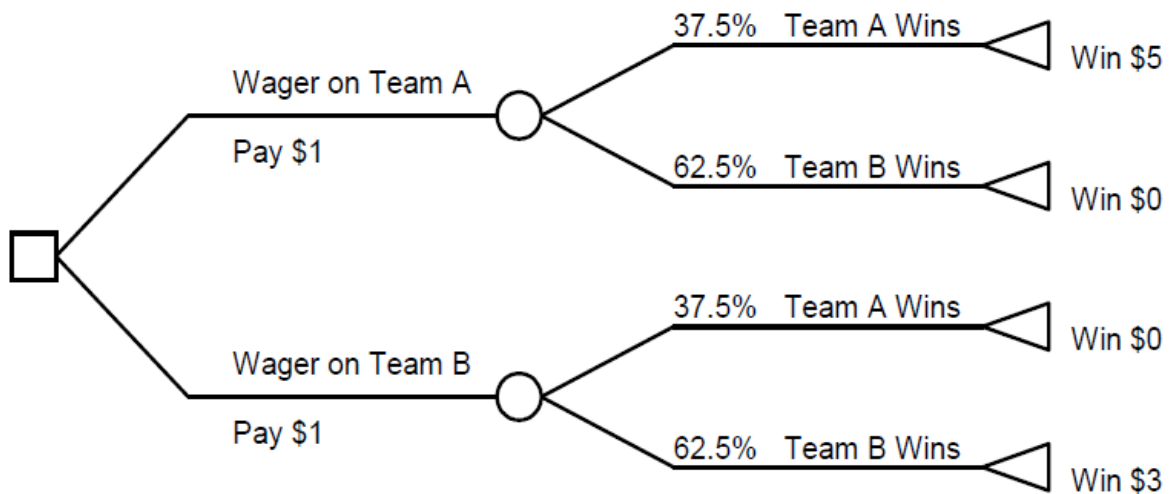


Figure 20: Decision Tree Example (Palisade, 2010)

The tree must represent the actual events as far as possible in order for the model to be as complete as possible. According to the Precision tree users guide (Palisade, 2010), the guidelines for decision trees include:

- The decision nodes should be clear so that only one option may be chosen at every node and the option is described
- Define the chance nodes so that they are mutually exclusive and collectively exhausted
- The tree should be represented in a chronological order from right to left

To perform the decision analysis one must complete a designed model and defined parameters. The decision model provides statistics, graphs and policy suggestions. To solve the decision tree, the folding back method is followed:

1. Chance node reduction: calculate the expected value (summation of the payoff multiplied by the probabilities) of the rightmost chance nodes and reduce to a single event.
2. Decision node reduction: choose the optimum path of the rightmost decision nodes and reduce to a single event.
3. Repeat: repeat step one and two if there are nodes that have not been analysed.

2.4.3 Risk Analysis

To manage a risk one has to first understand the risk. The best way to understand the risk is to apply risk analysis. It helps to control the risk in a cost effective manner. (Anon., n.d.) The main purpose of risk analysis is to assist the person making the decision with the necessary information regarding the probability of a loss. As a result it is critical that the user accept the risk analysis methodology and the results it delivers. (Anon., 2012)

The risk analysis method is used in the mining industry. An investigation was performed on the mining investment risk analysis based on a Monte Carlo simulation. The analysis provides guidance in exercising judgement on the degree of the risk. To solve the problem, a Monte Carlo simulation was built. The procedure was accomplished by computer software and a sufficient sampling process. The result of the model was to provide the investors with recommendations and investment advice. (Wei, et al., 2011)

Another mine risk evaluation was done at a gold mine. The mine was planning to open a small underground mine. The geological study was done, but it still contained some uncertainty regarding the size of the ore body. The analysis claimed to be an uncertain project life. These uncertainties included capital, mining costs, production rates, gold price, ore grades, working capital, and recoveries. The goal was to value the mining project on a discount cash flow basis, taking the impact of the economic and geological uncertainties into account. (Heuberger, 2005, p. 76)

In conclusion it is clear that risk analysis is used in other mining problems. This provides justification for the use of this methodology as a problem solving tool.

After developing a decision tree and determining the optimum path, a risk profile must be constructed in order to quantify the consequence of the path selected. A risk profile is a distribution function describing the chance involved with every possible outcome of the decision model. The risk profile graphically demonstrates uncertainty of the decision. The steps of a risk profile include (Palisade, 2010) :

- For a cumulative payoff tree, the tree is reduced by multiplying the probabilities on sequential chance branches. The diagram below illustrates an example of chance node reduction.

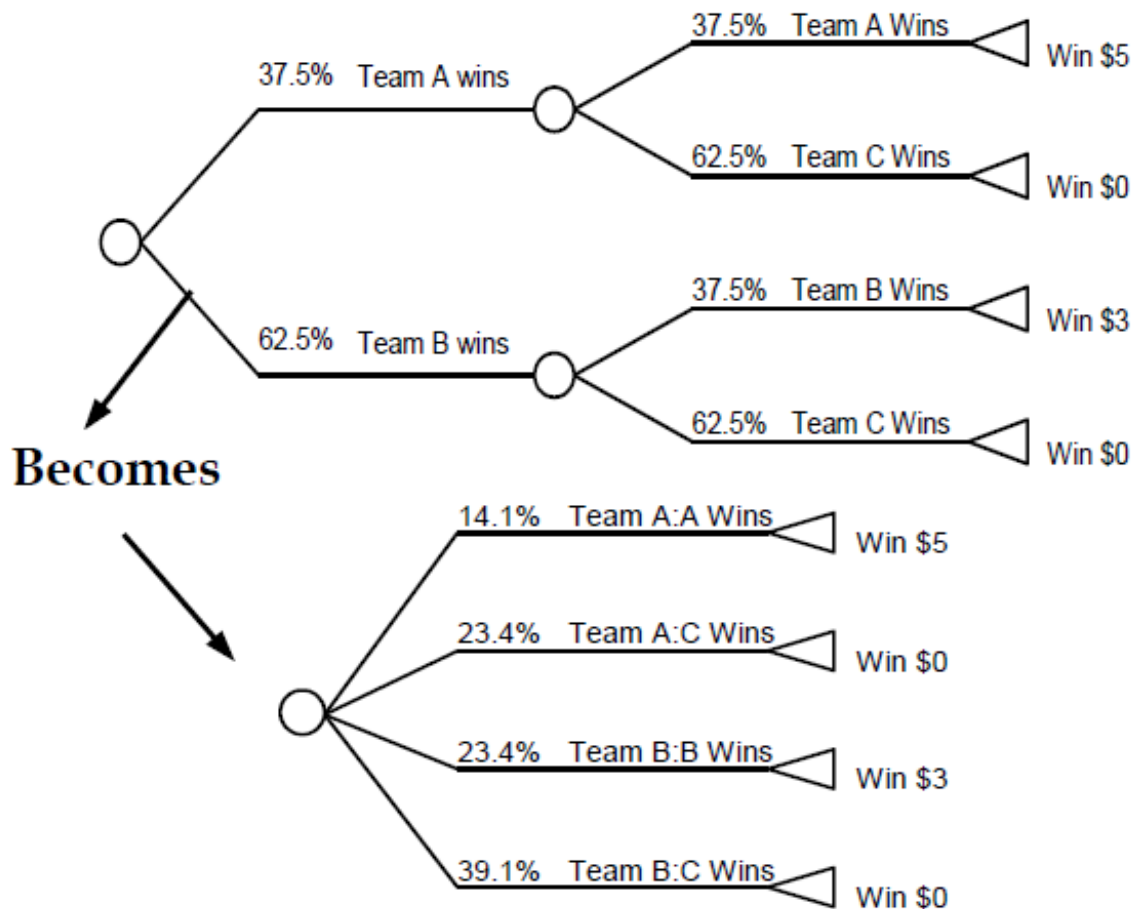


Figure 21: Example of a Chance Node Reduction

- The decision nodes are reduced by looking only at the optimal branches. The diagram below depicts decision node reduction.

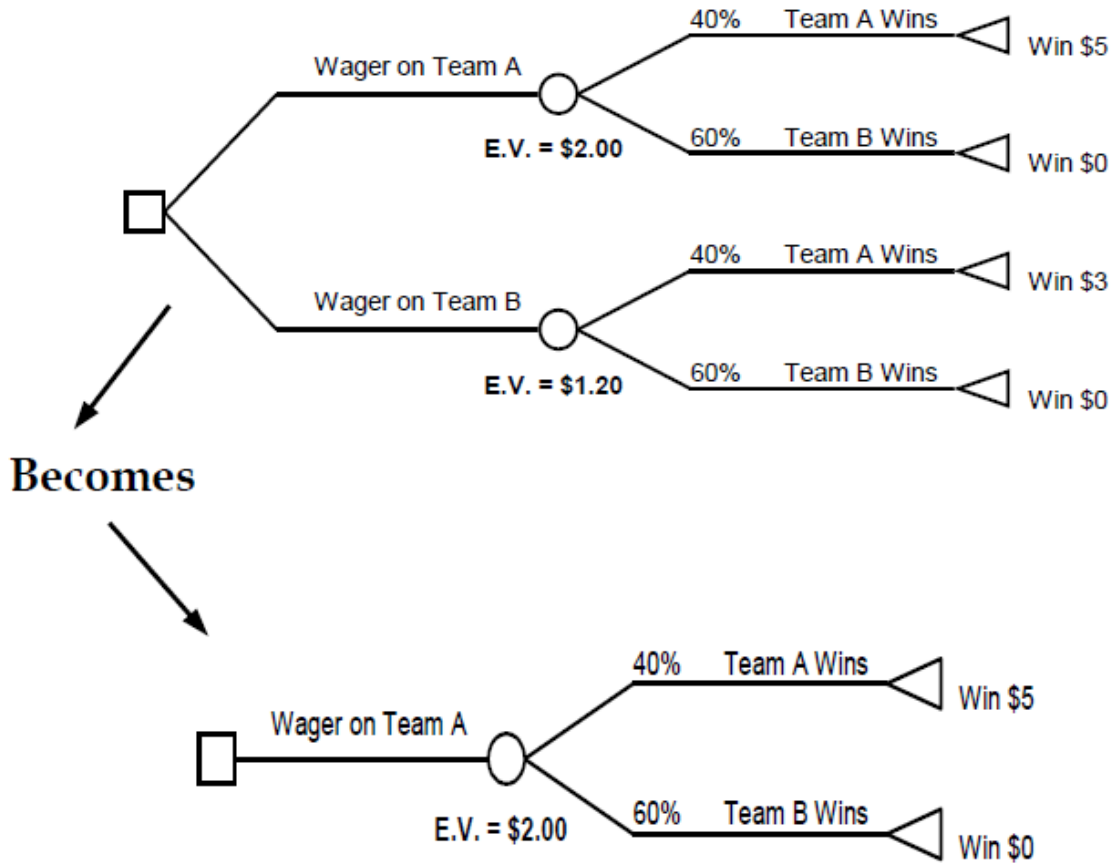


Figure 22: Example of Decision Node Reduction

3. These steps are repeated until the decision tree is reduced to a single chance node with a set of values and corresponding probabilities. The diagram below illustrates a single chance node.

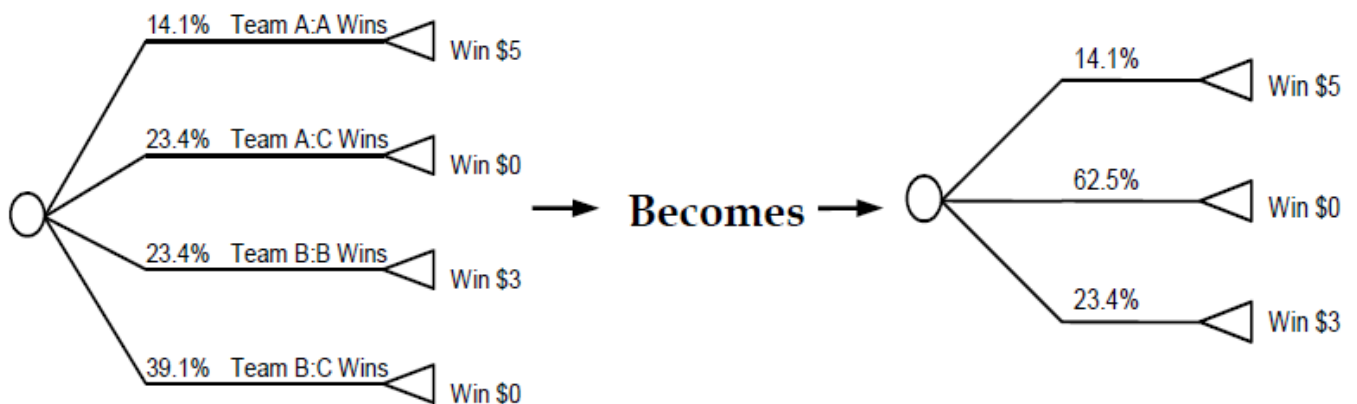


Figure 23: Example of a Single Chance Node

4. The final set of single chance nodes defines a discrete probability distribution which is used to construct the risk profile. The diagram below demonstrates an example of a probability chart and a cumulative chart.

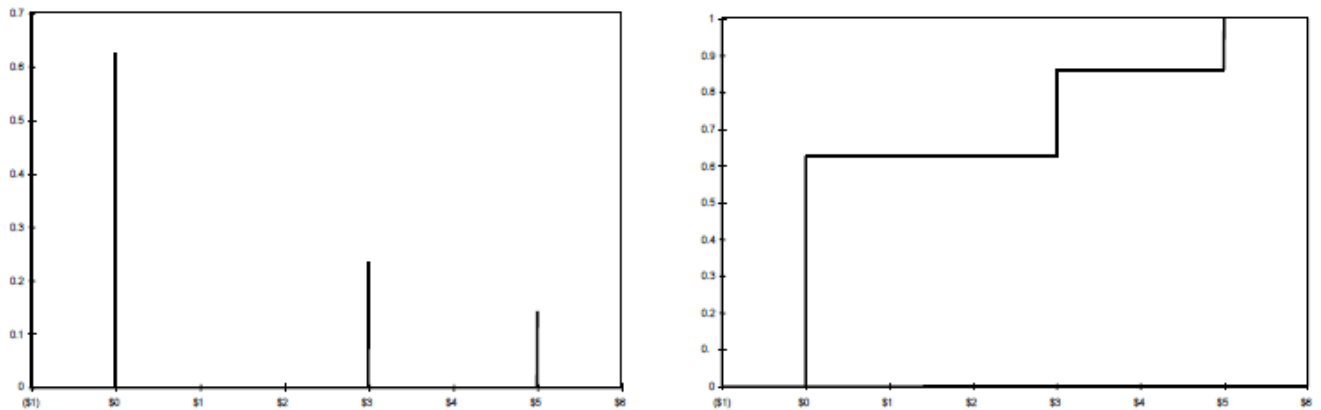


Figure 24: Probability Chart and Cumulative Chart (Palisade, 2010)

2.4.4 Sensitivity Analysis

In order to determine what input variables in the model matter the most, one must complete a sensitivity analysis. This method can be used in decision trees and influence diagrams. The sensitivity analysis allows the user to evaluate the impact of changing one or more variables in the model. This mechanism is not used to determine an explicit answer but rather assist the user in understanding the model better. (Palisade, 2010)

The outcome of sensitivity analysis is presented in a graphical manner. There are various ways of running a sensitivity analysis. Each model provides different kinds of valuable information in order to understand the model better. (Palisade, 2010)

The following definitions contribute to the understanding of sensitivity analysis (Palisade, 2010):

- Input: value (payoff) or probability defined in the decision model
- Base case: the number entered the first time the decision was modelled - the most likely value
- Minimum: the lowest possible value this variable may obtain
- Maximum: the highest possible value this variable may obtain

- Steps: the number of equally spaced values across the minimum and maximum range

The following paragraphs introduce the use of one way sensitivity analysis, tornado graphs, spider graphs and two-way sensitivity analysis.

2.4.4.1 One-Way Sensitivity Analysis

This method evaluates the impact of a single input on the expected value of the model. This value can either be the payoff of an event or the probability of the chance node. In order to run a one-way sensitivity analysis, the upper and lower bounds of the input must be defined. (Palisade, 2010)

The calculations of the sensitivity analysis are done by substituting the minimum value with the base case values to calculate the expected value. After that the value of each step is substituted with the base case value to determine an expected value. (Palisade, 2010)

The result of a one way sensitivity analysis can be plotted on a graph. The X-axis indicates the selected input value and the Y-axis indicates the expected value. The diagram below depicts an example of a one-way sensitivity analysis. (Palisade, 2010)

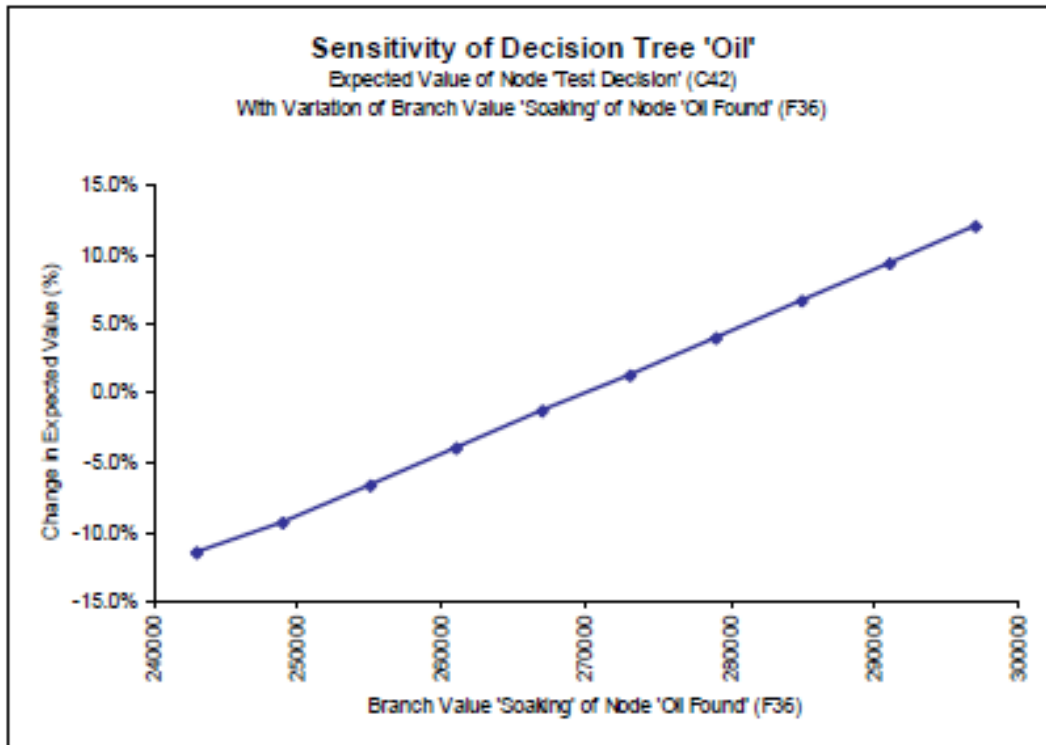


Figure 25: Sensitivity analysis One-Way Graph Example

2.4.4.2 Tornado Graph

The goal of a tornado diagram is to compare multiple analyses. The X-axis indicates the expected value and the Y-axis the different input values. The longest bar refers to the input with the greatest impact on the sensitivity analysis. The diagram below illustrates an example of a tornado graph. (Palisade, 2010)

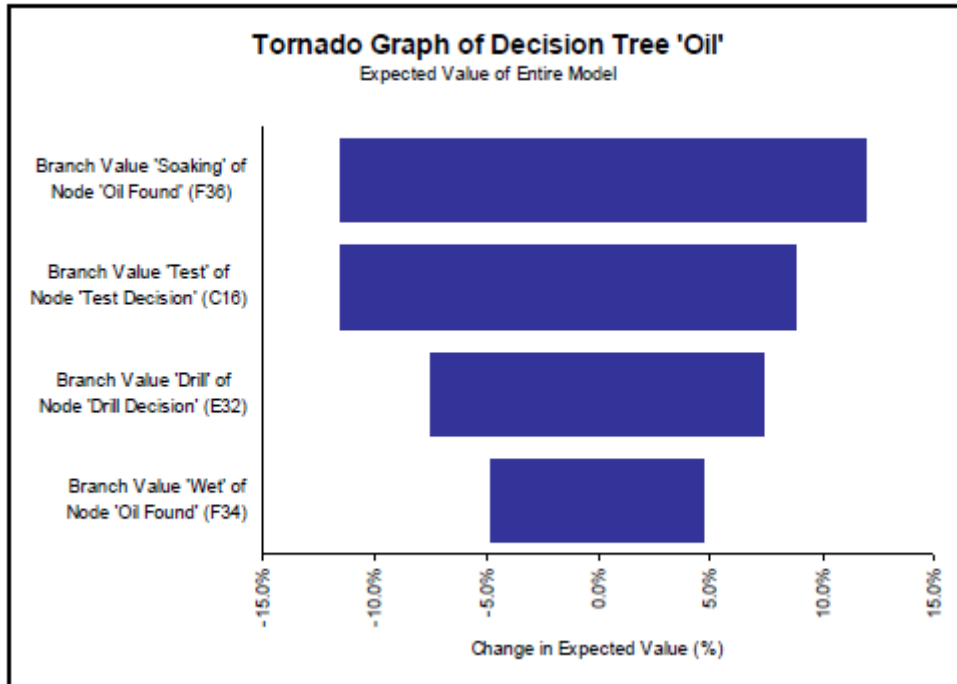


Figure 26: Tornado Graph Example

2.4.4.3 Spider Graph

The spider graph is also a method used to compare different inputs. The base case is plotted on the X-axis and on the Y-axis is the expected value. The slope indicates the relative change of outcome of each line. The curve depicts the linearity between the two variables. (Palisade, 2010) The diagram below illustrates an example of a spider diagram.

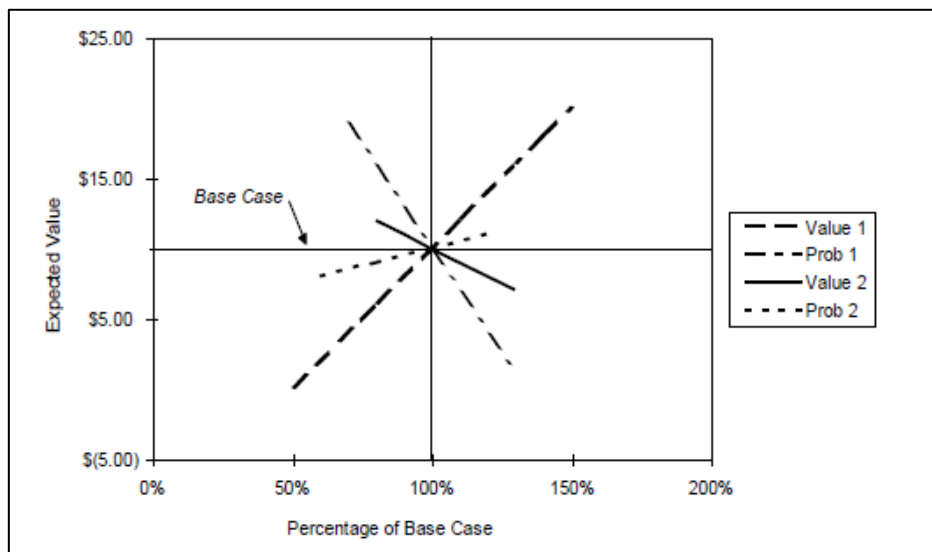


Figure 27: Example of a Tornado Graph

2.4.4.4 Two-Way Sensitivity Analysis

For a two-way sensitivity analysis, the effect of two inputs on the decision model is studied. Usually the most critical and important inputs are plotted. This graph is plotted on a 3D axis. The value of the first input is plotted on the X-axis and the value of the second on the Y-axis. The expected value is plotted on the Z-axis. The diagram below illustrates an example of a two-way sensitivity analysis.

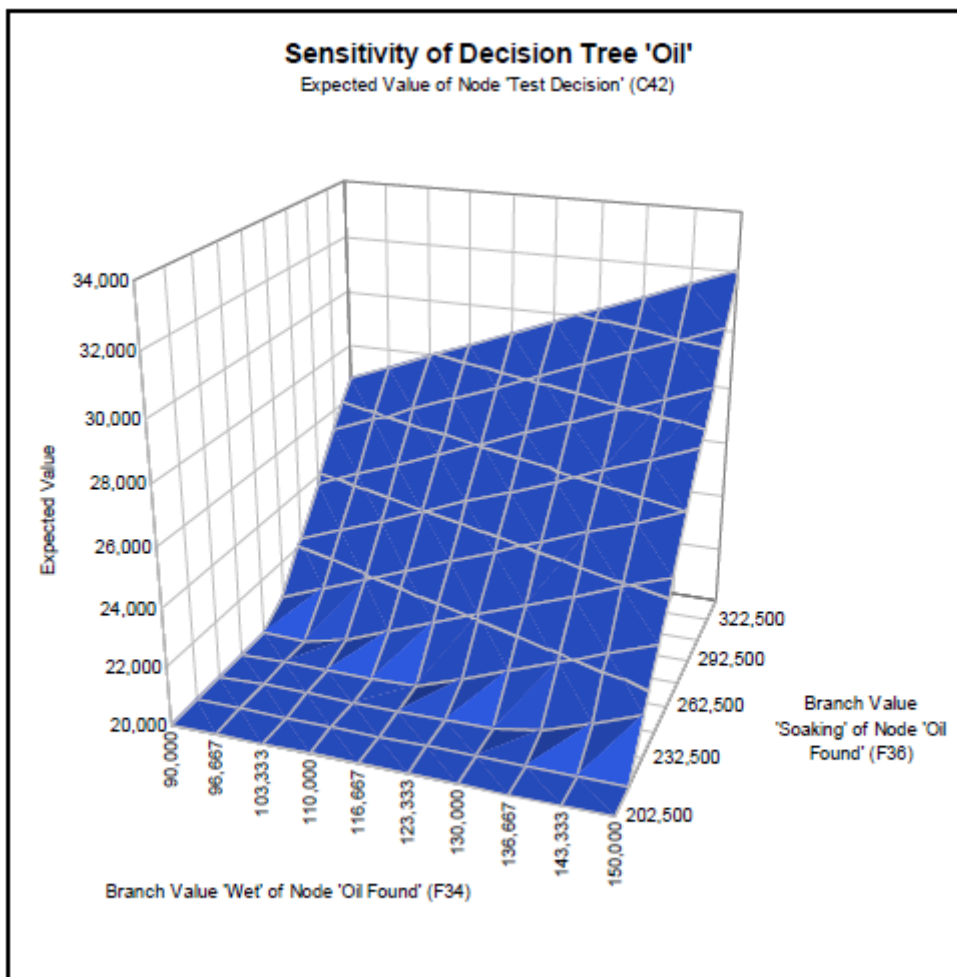


Figure 28: Example of a Two Way Sensitivity Analysis

2.4.5 Monte Carlo Simulation

In the real world, input variables in a model are subject to uncertainty. The Monte Carlo is handled with situations in which uncertainty abounds. The goal is to represent the uncertainty surrounding of the possible inputs for different alternatives. (Robert T. Clemen, 2001) The first step in building a Monte Carlo simulation is to capture the uncertainty in the model by generating random numbers. The random numbers can be defined by various distributions. These distributions include uniform, triangular, normal, exponential, etc. The input and output data is captured in a data table in Excel. This data is inserted into the model and delivers an output.

The Monte Carlo simulation can be used to perform sensitivity analysis. This strategy can be performed by calculating the correlation between the various inputs and their output.

The diagram below illustrates the methodology applied in Monte Carlo simulation.

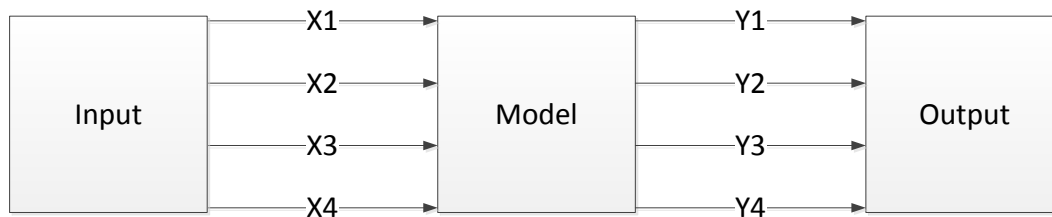


Figure 29: Monte Carlo Simulation

2.4.6 Value of Information

The definition of value of information is the amount a person making a decision is willing to pay for the information before making the decision. Often there is an option in a decision to gather additional information. There is a procedure to determine when it will be worth collecting this extra information. (Kirkwood, n.d.)

The procedure starts by determining the value of perfect information. The perfect information eliminates all the uncertainty about the outcomes for the decision options. In real world there is seldom a situation where no uncertainty is involved. This is the reason why the perfect information represents the worth of gathering additional information. If all the alternatives for

collecting information cost more than the value of perfect information, then these alternatives are not considered anymore. As a result imperfect information cannot be worth more than perfect information. (Kirkwood, n.d.)

The diagram below depicts the development of imperfect information to perfect information by adding additional information. The information added has a certain value.

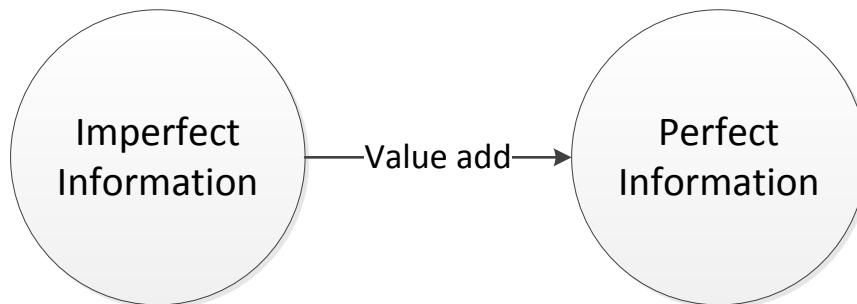


Figure 30: Value of Information

2.5 Summary

This chapter discussed all the literature required to see where this project fits into the bigger picture. It provides a holistic approach to the project. Each of the sections that were discussed, has a certain impact on the problem statement. The geological exploration data, production planning, and stoneworks operations must be in place in order to prevent the stoneworks process from having a drastic impact on the required production volumes.

The second part of this chapter focussed on the industrial engineering mechanisms required to develop the problem statement. Each of the methodologies required was investigated and analysed. These methods can now be developed further into usable structures to provide solutions strategies to the problem statement.

In conclusion, there are various factors which can have an impact on mine planning. In this project the focus is only on the impact of the stoneworks process on the mine plan. During the investigation it also became clear that there are various factors which may have an impact on the productivity of the stoneworks process. These factors may cause the stoneworks process to become a bottleneck.

Chapter 3 Design

This chapter discusses the stages of development and the final design of the model. The flow chart below is a general model approach. This diagram shows the steps that need to be taken to complete the building of a model. The flow chart is used in the project to indicate the flow of progression of the model building.

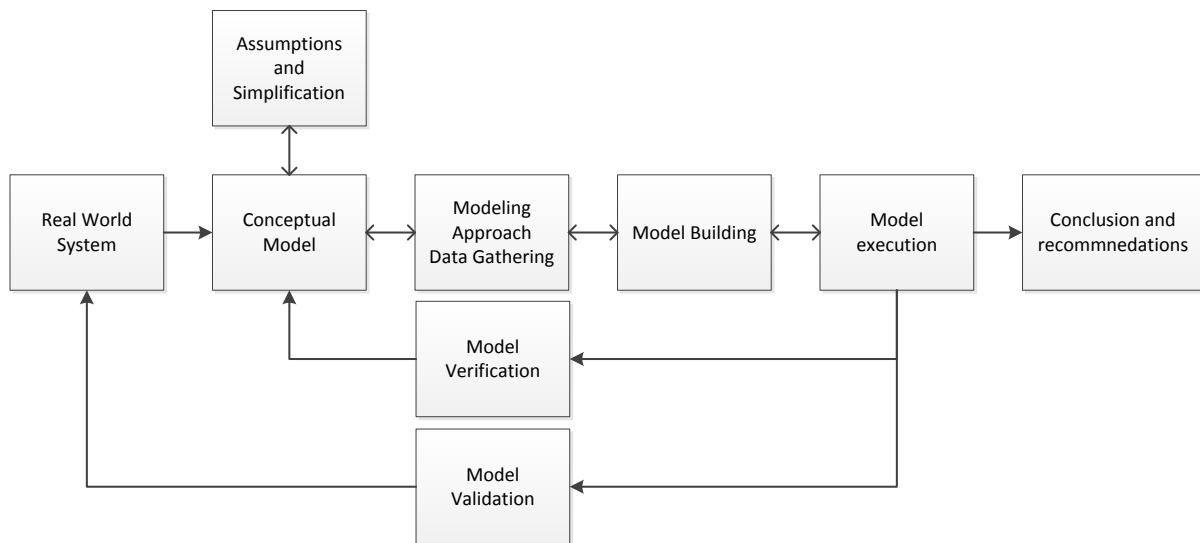


Figure 31: General Model Approach (Kruger, 2013)

3.1 Stages of Development

The project went through different stages to finally achieve the optimum approach to the problem. The goal was to discover alternative scenarios in order to develop a solution to the problem. The first stage was the geological exploration and data analysis, and the second stage was the development of the quantification of imperfect information. The latter methodology was developed further into a model. The following section discusses these different stages.

3.1.1 First Stage of Development: Geological Exploration and Data Analysis

The first approach was to analyse the geological exploration data. Data was captured and inserted into a probability tree.

The data that was collected are the coordinates of the structures in the ore body. This data was collected at ABC Colliery. For each data point the vertical drilling coordinate, horizontal drilling coordinate and actual data coordinate was collected. The next step was to calculate the distances from the drilling point to the actual position. From these distances it is possible to determine the probability for the forecasted coordinates to deviate from the actual position of the structure. These probabilities are the ones used in the probability tree.

The probability tree reflects how both vertical as well as horizontal drilling can deviate from the actual position. This method was not developed into a usable model because of its lack in tangible deliverables. The probability tree is only a summary of an existing situation and does not deliver an output. The development for the project then moved to stage two. Appendix A shows the probability tree and the data analysis.

3.1.2 Second Stage of Development: Quantification of Imperfect Information

The table below indicates the consistency in stage two. This states that the problem and the output are related to each other.

Problem	Aim	Scope	Data Gathering	Model	Outcomes
Impact of stoneworks on production volumes delivered	Capture the imperfect information scenario. Determine the impact of production losses caused by imperfect information	Analyse the stoneworks process and the consequences of imperfect information.	Probability of burnt coal, available pit room, explosion in the case of burnt coal and the thickness of dykes	Decision tree indicating the expected value of unforeseen dyke	Sensitivity analysis. Model validation. Cost of imperfect information. The value added by perfect information

Table 1: Consistency Matrix

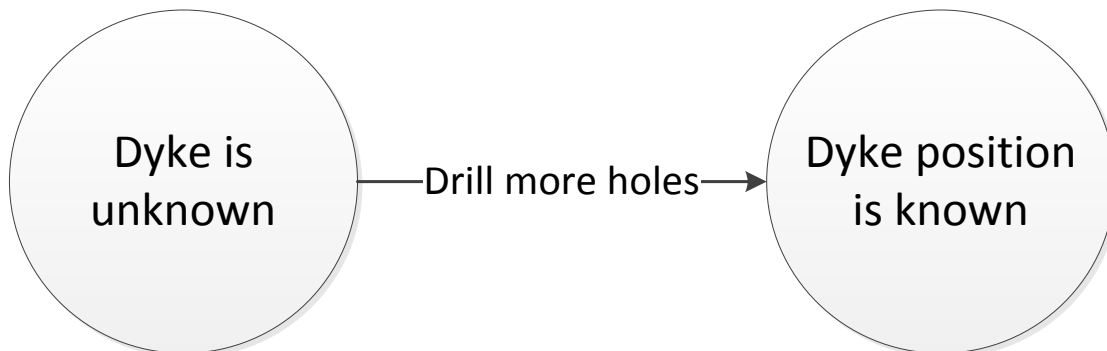


Figure 32: Value of Information: Problem Specific

The diagram above indicates the concept of value of information based on the problem stated in this project. The imperfect information phase in the cycle is when the position and/or the presence of the dyke is not known. To reach more accurate or perfect information more holes must be drilled in order to increase the level of confidence. The second stage of development investigates the cost or expected value of an unforeseen dyke; similarly the imperfect information scenario. The imperfect scenario is thus a justification for the amount of holes that can be drilled per year.

There is a trade-off between drilling more holes and the actual advantage obtained if the holes are drilled. The risk of an unforeseen dyke can be minimised by drilling more vertical and horizontal bore holes in order to attain a more accurate position of the dolerite intrusions. The benefit is to minimize the risk which leads to more accurate planning and consequently reduced stoneworks bottlenecks. In order to achieve more accurate positions of the dolerite intrusions, additional costs are involved. The goal is to determine the optimal point between the benefit or the potential accuracy and the additional cost. The graph below depicts the break-even point between the cost and the risk advantage.

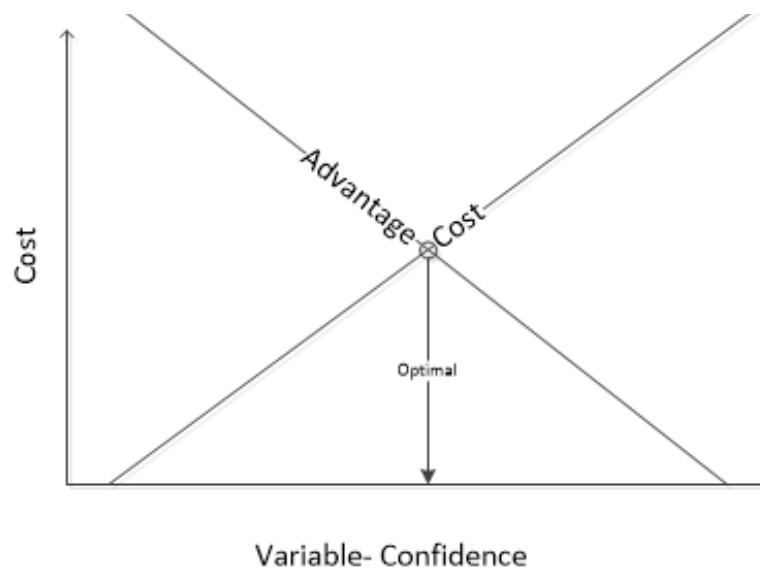


Figure 33: Trade-off Graph

Monte Carlo simulation is used to make provision for the uncertainty in the model. The diagram below is an illustration of the Monte Carlo simulation model. The goal of this diagram is to provide the user with a better understanding of the logical reasoning behind the model. The simulation consists of three main parts namely input, model and output. The diagram shows the 23 inputs with triangular distributions, the model being a decision tree and the output being the expected value of the decision tree. The following section elaborates on the three main parts of the model in to explain the reasoning.

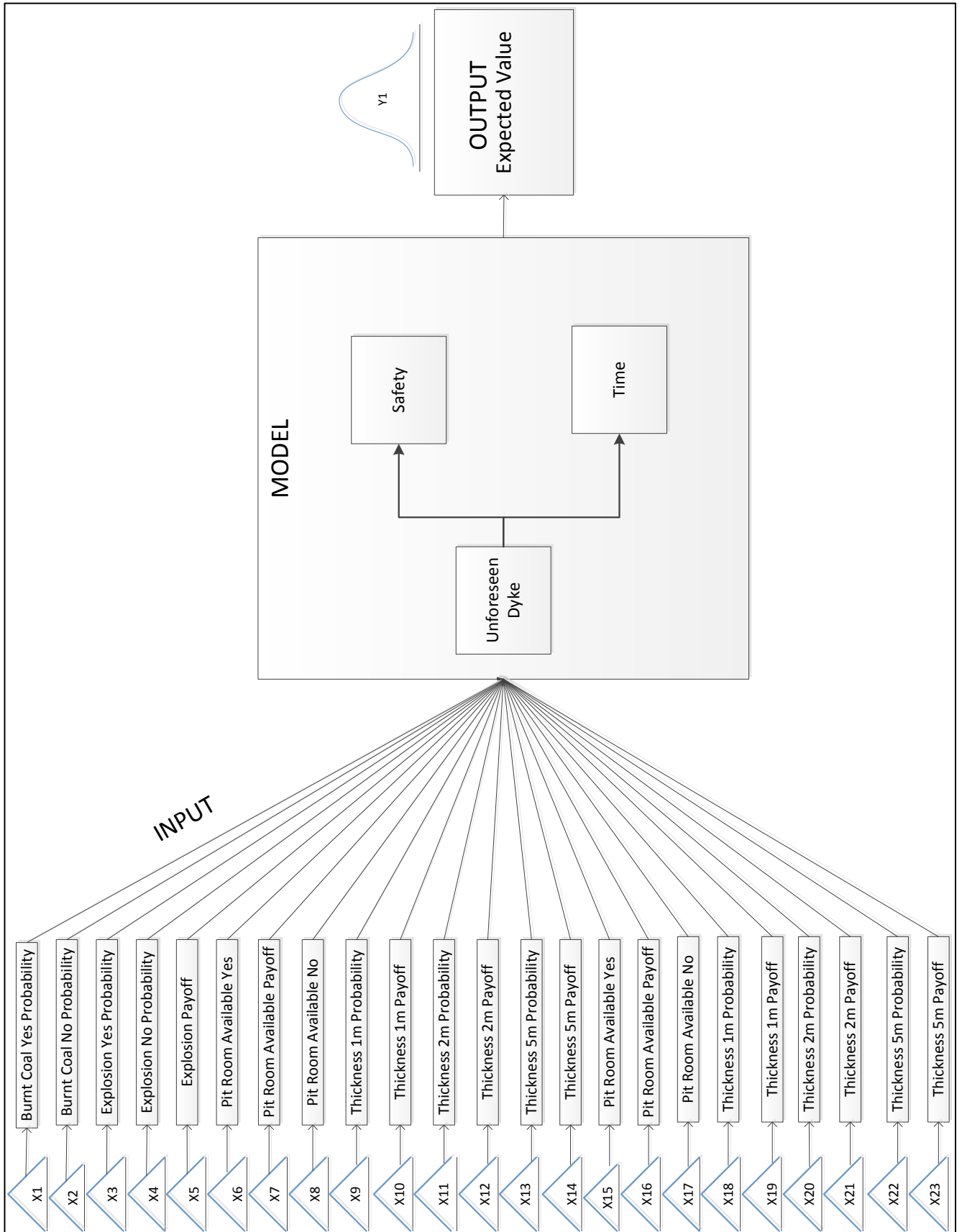


Figure 34: Monte Carlo Simulation Model

3.1.2.1 Input

The flow chart below is an indication that the model has reached the modelling approach, assumptions and simplification phases (indicated with yellow). These phases are discussed in this section.

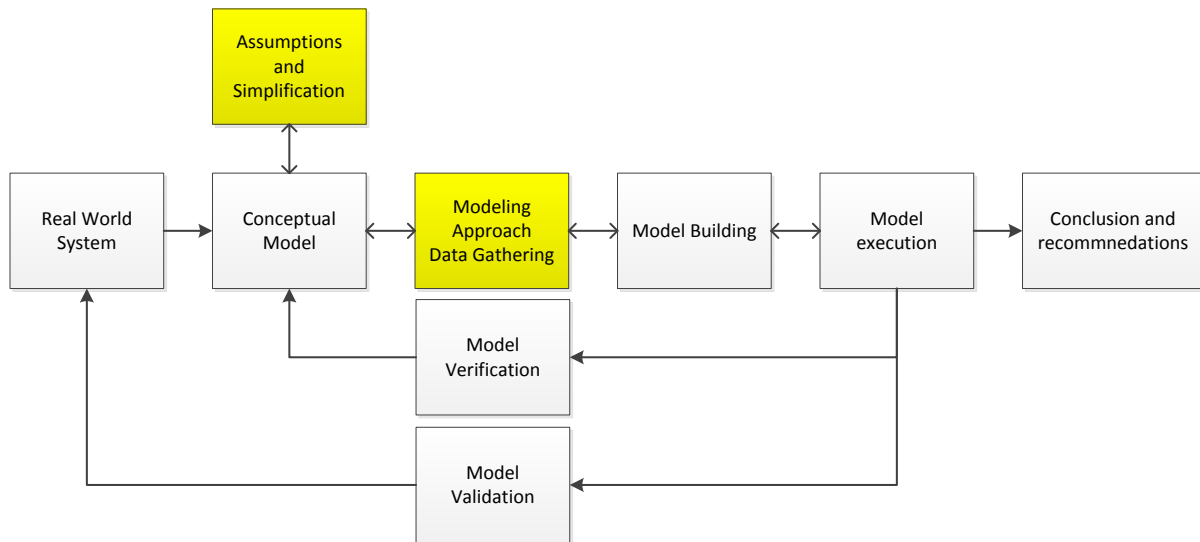


Figure 35: General Model Approach - Assumptions (Kruger, 2013)

There are 23 input variables in the decision tree model, some of which are reciprocal. The data consists of probability of occurrences and pay-offs. The data of each of the variables was gathered at ABC Colliery. It is important to realise that data on the stoneworks process is limited in the mining industry, since it is not a quantified area. Because the data is scarce, assumptions had to be made in order to calculate the input data. The table below provides the user with valuable information on each variable. The information includes:

- The description of the variable. The number of the variable correlates with diagram 36 so that the user can identify which variable is discussed in the decision tree model.
- The method by which the variable is calculated. The formula is in the table.
- The assumptions required to calculate the variable.
- The unit of measure of the variable. The goal is to get all the variables in the same unit, to finally get one unit as an output.

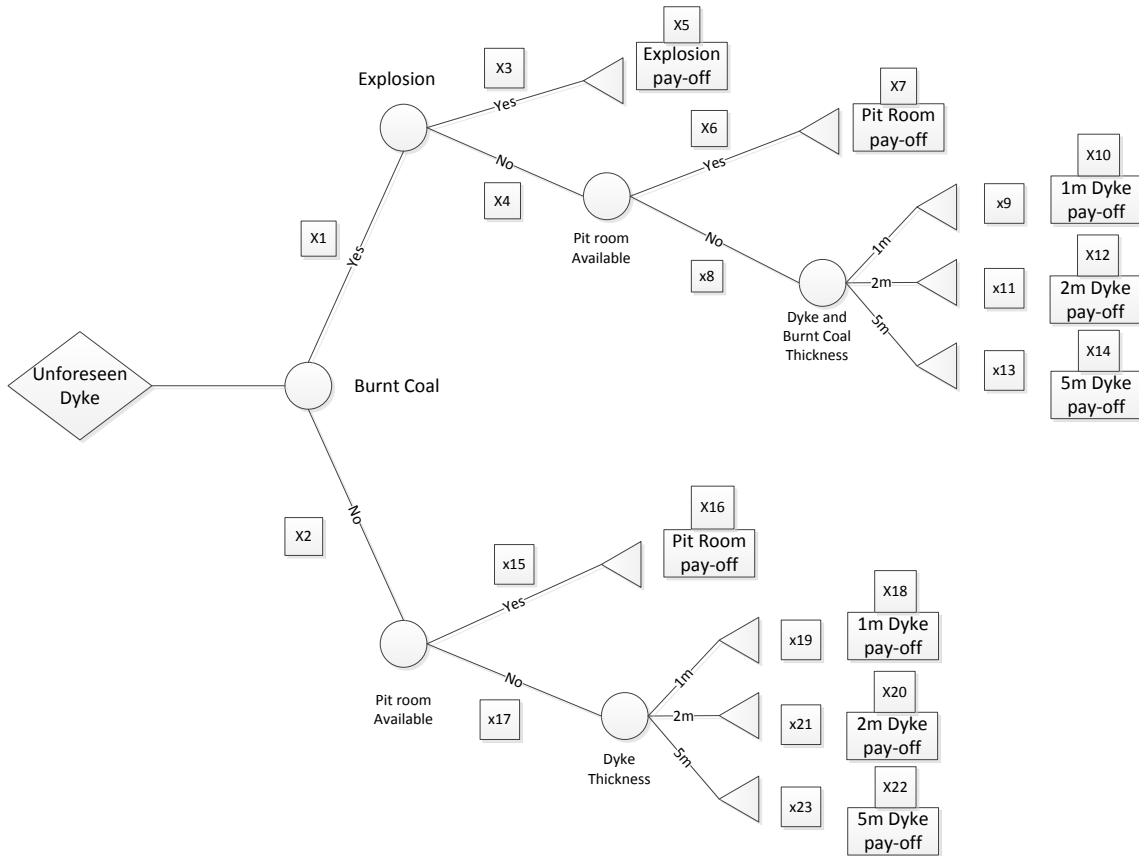


Figure 36: Input Variables

Input Variables				
Variable				
Number	Description	Calculation	Assumption	Unit
X1	Burnt Coal Yes Probability	= Dyke with burnt coal/ total dykes	-Extraction of two years' geological data	
X2	Burnt Coal No Probability	=Dyke without burnt coal/ total dykes	-Extraction of two years' geological data	
X3	Explosion Yes Probability	= number of explosions in 30 years/ (number of CM on complex * number of shifts per year * 30 years)	-Two explosions in 30 years - 50 continuous miners on mining complex -495 shifts per year	Explosions per 30 years
X4	Explosion No Probability	= 1- X3	-Two explosions in 30 years - 50 continuous miners on mining complex -495 shifts per year	No explosions for 30 years
X5	Explosion Pay-off	=Look value up in risk matrix	-Use 7*7 Risk Matrix	Rand

			-mine out of use for 3 months - 5 sections	
X6	Available Pit room Probability	=1-X8	- average number of shifts per month is 40.7 -3 weeks of lower productivity shifts	Number of shifts with pit room per year
X7	Pay-off Pit room available	= 1shift * Rand/Ton * Ton/shift	-Loss of one shift for unplanned move -average R/ton -average ton/shift	-Rand/shift
X8	No available pit room probability	=(occurrences* weeks down *shift/week)/ (sections* months*shift/month)	-average number of shifts per month is 40.7 -3 weeks of lower productivity shifts	Number of shifts without pit room per year
X9	Probability 1m dyke thickness and Burnt coal	= (number of dykes between 0-1 meters with burnt coal)/ total of dykes with burnt coal	- Extraction of two year's geological data	- Data for two years
X10	Pay-off 1m dyke thickness and Burnt coal	= ([burnt coal + dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blast per shift -average R/ton -average ton/shift	-Rand/shift
X11	Probability 2m dyke thickness and Burnt coal	= (number of dykes between 1-3 meters with burnt coal)/ total of dykes with burnt coal	- Extraction of two years' geological data	- Data for two years
X12	Pay-off 2m dyke thickness and Burnt coal	= ([burnt coal + dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blasts per shift -average R/ton -average ton/shift	-Rand/shift
X13	Probability 5m dyke thickness and Burnt coal	= (number of dykes between 3-6 meters with burnt coal)/ total of dykes with burnt coal	- Extraction of two years' geological data	- Data for two years
X14	Pay-off 5m dyke thickness and Burnt coal	= ([burnt coal + dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blasts per shift	-Rand/shift

		R/ton	-average R/ton -average ton/shift	
X15	Available Pit room Probability	=1-x17	-average number of shifts per month is 40.7 -3 weeks of lower productivity shifts	Number of shifts with pit room per year
X16	Pay-off Pit room available	= 1 * Rand/Ton * Ton/shift	-Loss of one shift for unplanned move -average R/ton -average ton/shift	-Rand/shift
X17	No available pit room probability	=(occurrences* weeks down *shift/week)/ (sections* months*shift/month)	-average number of shifts per month is 40.7 -3 weeks of lower productivity shifts	Number of shifts without pit room per year
X18	Pay-off 1m dyke thickness	= ([dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blasts per shift -average R/ton -average ton/shift	-Rand/shift
X19	Probability 1m dyke thickness	= (number of dykes between 0-1 meters without burnt coal)/ total of dykes with burnt coal	- Extraction of two years' geological data	- Data for two years
X20	Pay-off 2m dyke thickness	= ([dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blasts per shift -average R/ton -average ton/shift	-Rand/shift
X21	Probability 2m dyke thickness	= (number of dykes between 1-3 meters without burnt coal)/ total of dykes with burnt coal	- Extraction of two years' geological data	- Data for two years
X22	Pay-off 5m dyke thickness	= ([dyke thickness]/ meters advance per blast) * ton/shift * R/ton	- 1.8 m advance per blast - 2 blasts per shift -average R/ton -average ton/shift	-Rand/shift
X23	Probability 5m dyke thickness	= (number of dykes between 3-6 meters	- Extraction of two years'	- Data for two years

		without burnt coal)/ total of dykes with burnt coal	geological data	
--	--	---	-----------------	--

Table 2: Input Variables

3.1.2.2 Model

The flow chart below indicates the progression to the next phase, model building (indicated with yellow). The subsequent section discusses the model building phase.

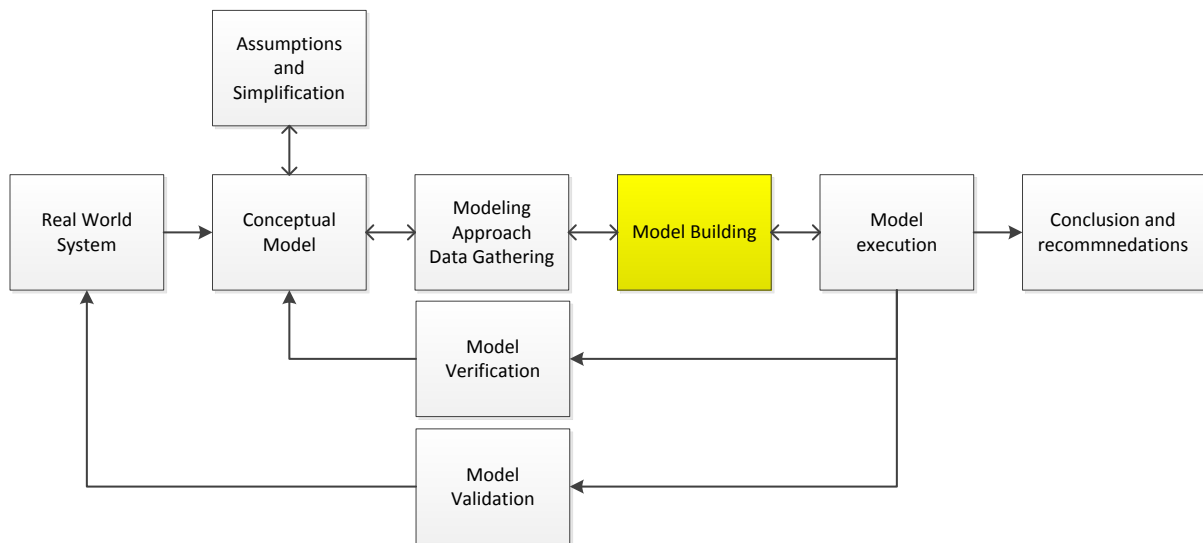


Figure 37: General Model Approach - Model Building (Kruger, 2013)

The modelling technique used, is a decision tree model. This model technique is an excellent way to capture the information of the data analysis and deliver a usable and tangible result. This model quantifies the production risk in the mine planning process and delivers a value that justifies the amount of drilling per year. This generated value provides a solution to the problem statement. The model was built in Excel. This program has all the necessary statistical formulae required to build the decision tree model.

The Monte Carlo simulation was also applied to the decision tree model to capture the uncertainty of each variable. The Precision tree program was used to test and validate the model. The following section will discuss how the decision tree model was built and the steps followed in order to develop the Monte Carlo simulation.

3.1.2.2.1 Decision Tree Layout

The branches in the diagram below are numbered from 1-14. The paragraph below the diagram discusses each of these branches of the decision tree in order to understand the logical reasoning behind each branch and node.

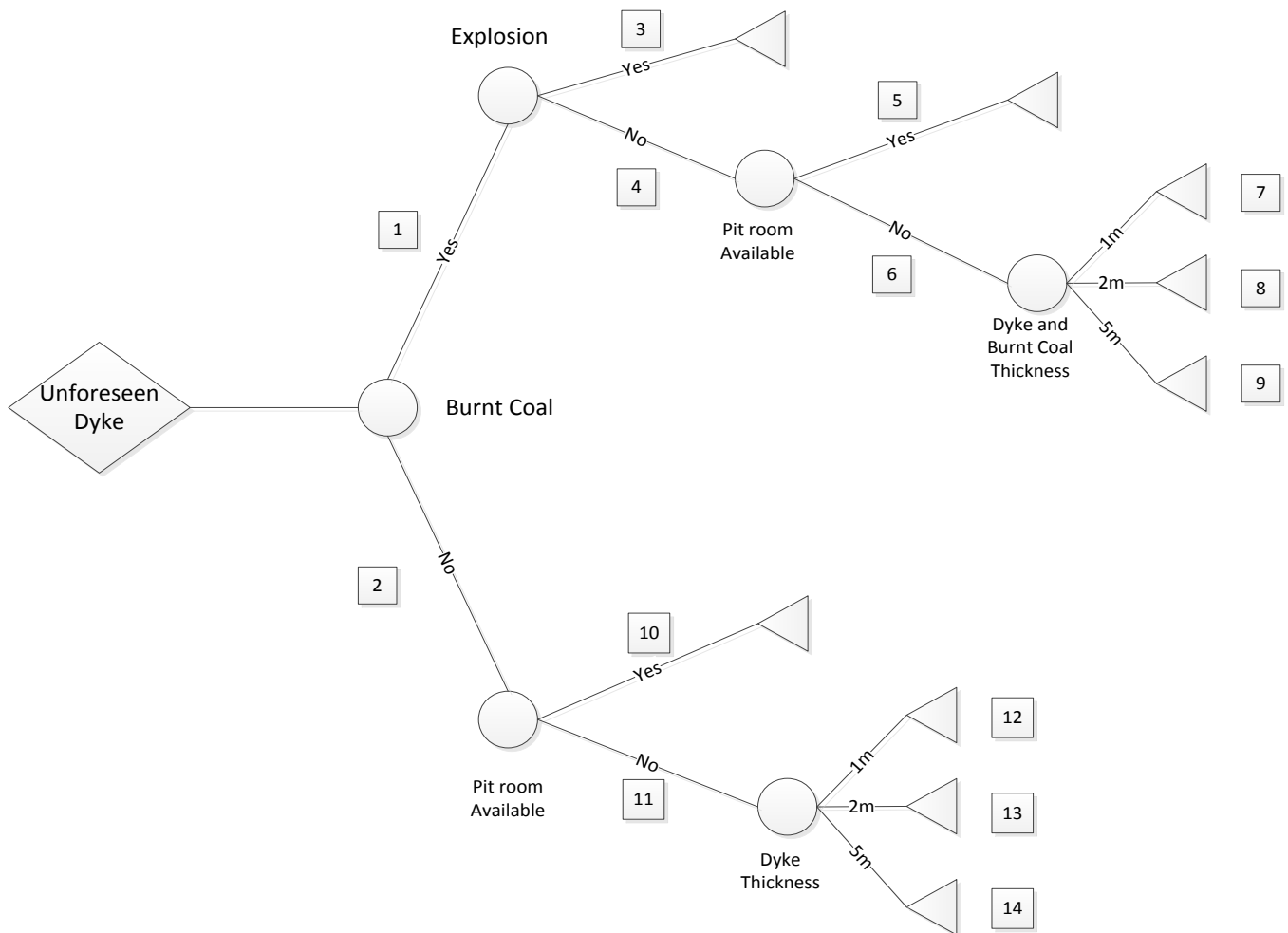


Figure 38: Decision Tree Layout

There is a possibility that an unforeseen dyke, not taken into account in the mine plan, may be reached. There are two entities that will be impacted when such a dyke is reached, namely safety (branch one) and time (branch two). To divide the tree into definite branches (one and two), the question that must be answered is whether burnt coal is present or not. If burnt coal, caused by intrusion of dolerite, is present there is a possibility of a safety hazard. If the burnt coal is not handled correctly it can cause an explosion. Branch one is split into two parts by answering whether the burnt coal has caused an explosion. If there is no

explosion, the next question to ask, is whether alternative space, also known as pit room, is available for mining. This is indicated by branches five and six respectively. Branch six is when there is no pit room available. In such a case the thickness of the dyke will determine the time required to remove the dyke. This then leads to branches seven to nine. The opposite side of the tree - branch two – indicates a situation where there is no burnt coal thus only the time aspect will be influenced. Again branch two is divided by the question whether there is pit room available. This leads to branches ten and eleven. Branch eleven is categorised by the thickness of the dykes, which will determine the time required to remove the dyke.

3.1.2.2.2 Monte Carlo Simulation

A Monte Carlo simulation was built in order to capture the uncertainty in the model. The first step was to generate random variables for the input data. A random triangular distribution was generated for each input variable. The base value was used as the most likely and the minimum and maximum values are respectively minus and plus ten per cent lower or higher than the base case value. The second step was to calculate the expected value of the decision tree and the last step to generate multiple expected values to capture the variation in the output. This simulation was run 10 000 times.

3.1.2.3 Output

The model has multiple outputs. These outputs include the expected value of the decision tree model and the sensitivity analysis of the Monte Carlo simulation. The expected value distribution is also captured in Bestfit program.

The expected value is the output of the decision tree model. It delivers the cost of imperfect information and justifies the cost of drilling. The expected value is calculated by summing the payoffs multiplied by the probabilities. This was all computed in Excel. The formula below depicts the expected value calculation:

$$Expected\ value = \sum (pay\ off \times probability)$$

The Monte Carlo simulation is used to build sensitivity into the model. Each input variable is correlated to the expected value. This method is applied to determine whether there is any correlation between the expected value and the input values. The result of the correlation coefficient will indicate which input variables are the most sensitive to the expected value.

3.2 Final Design

The flow chart below indicates the progression to the next phase, namely the model execution phase. This section elaborates on the model execution.

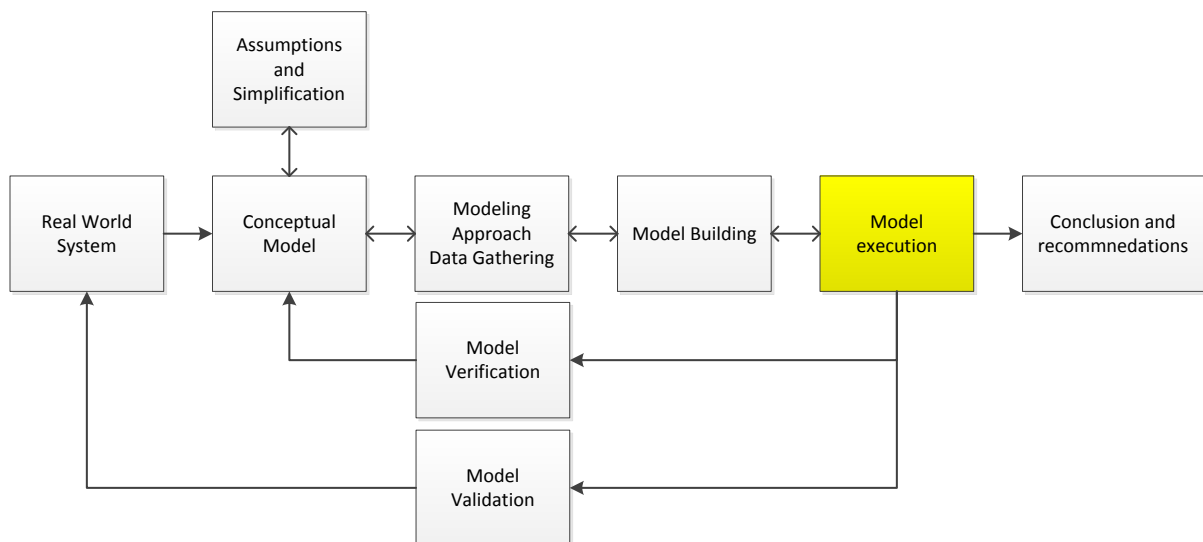


Figure 39: General Model Approach - Model Execution (Kruger, 2013)

The diagram below depicts the screenshot of the final decision tree model built in Excel. This model was used to generate multiple expected values of imperfect information. The result is captured in a Monte Carlo simulation.

Chapter 4: Solutions and conclusions

This chapter discusses the findings of the project. It also provides the conclusion of the project and possible future endeavours.

4.1 Results

As stated in the aim of the project, the objective is firstly to deliver the cost of imperfect information and secondly to determine the tons of coal lost due to an unforeseen dyke. The following section will discuss these findings as well as the result of the sensitivity analysis.

4.1.1 Sensitivity Analysis

The following graph illustrates, in the form of a tornado diagram, the sensitivity of each input variable. The variables are listed from the highest to the lowest sensitivity. As can be seen in the graph variable x8, the probability of no available pit room is the most sensitive to the expected value. This entails that if the expected value or the risk increases, the probability of no pit room also increases. Variable x6, the probability of pit room, also has a strong relation to the expected value. But for this variable the probability of available pit room increases as the expected value decreases. The goal is to minimize the expected value since this value represents the risk involved, should an unforeseen dyke be reached. This implies that it is of the utmost importance to have sufficient pit room available in each section, since this will have an impact on the risk. It is not always possible to control whether there is pit room available or not. However provision for pit room can be enhanced by strategic planning. It would be advisable also to consider the first three variables: x17, x7 and x16. These three variables represent the pay-off if pit room is available. It is thus the potential production loss due to an unplanned section move.

In conclusion the potentially available pit room plays an enormous role in the risk, should an unforeseen dyke be encountered. It is thus advisable to pay special attention to this variable.

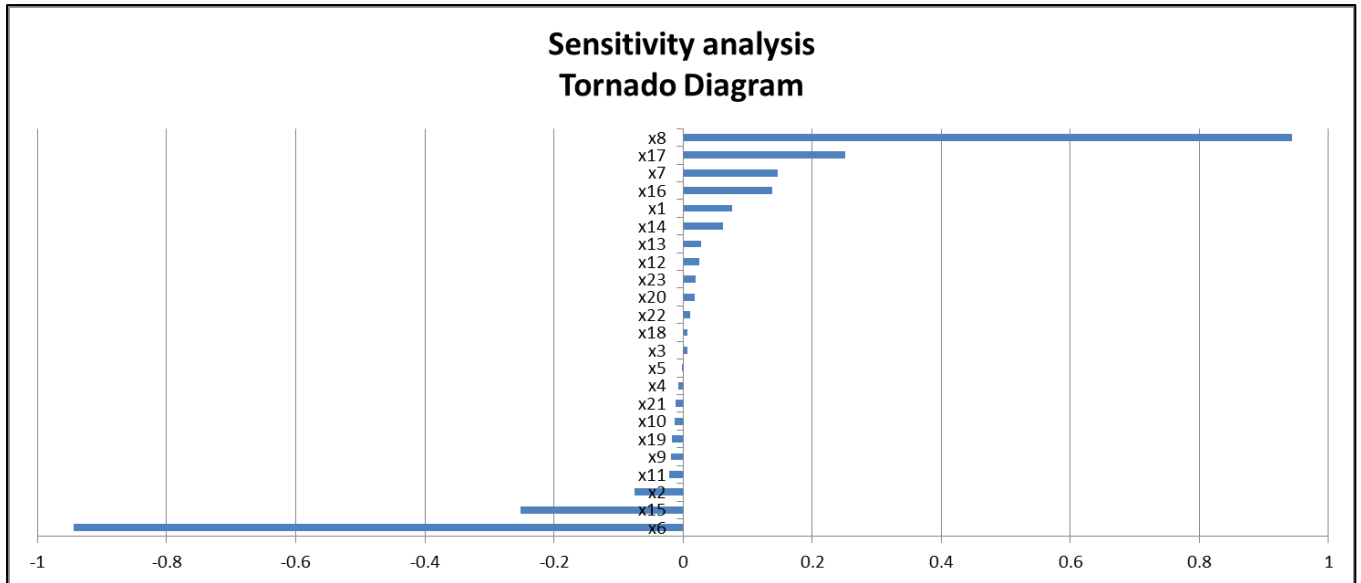


Figure 41: Tornado Graph

4.1.2 Imperfect Information

4.1.2.1 Cost of Imperfect Information

The results of the decision tree model are summarized below in a box plot and a fitted distribution of the expected values. The unit of the result is in R/shift. The value can be multiplied with the amount of shifts per year in order to get a value for the year. This result indicates the value of imperfect information and the maximum amount that can be paid to more accurately determine the position of a geological fault. This is the maximum amount that can be spent although it is not necessarily the total suggested amount that should be spent. This value can be useful for budgeting purposes. As a result, according to the decision tree model, the average potential production losses are 133 301 Rand per shift. The total amount per year is thus 65 164 229 Rand per year (489 shift per year in financial year 2013).

The box plot is an apt summary of the distribution of the expected value. The diagram shows that the median is 135 795 Rand per shift. The expected value has a minimum of 105405 and a maximum of 173 577 Rand per shift.

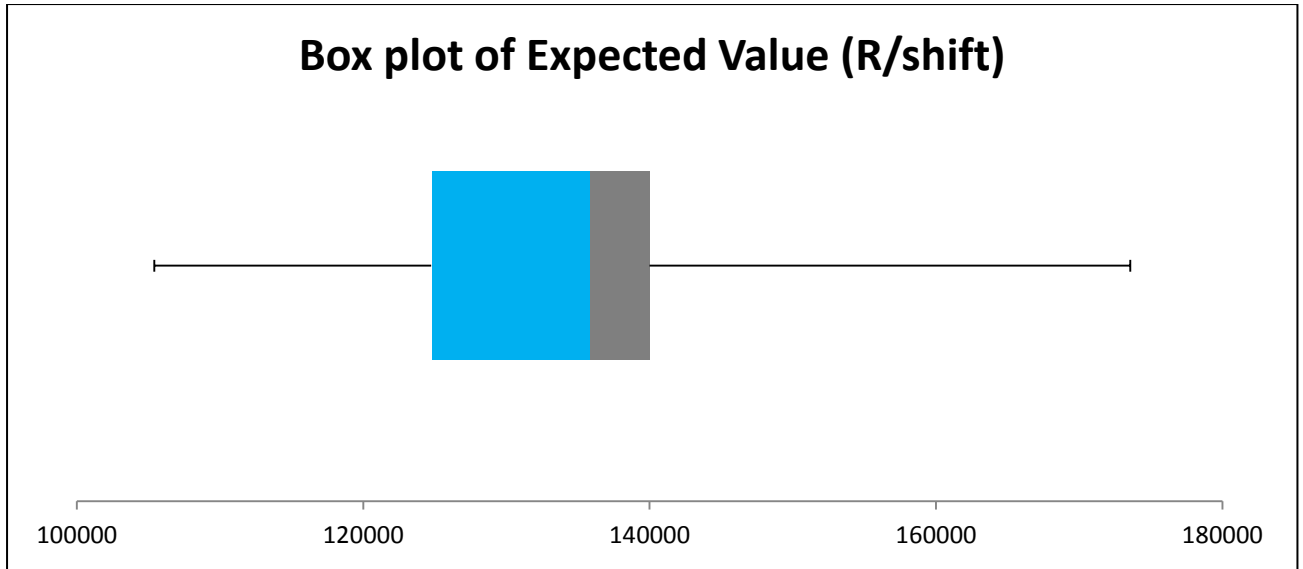


Figure 42: Box plot of Expected Value

Statistics (R/shift)	
min	105405.5
q1	124754.9
median	135795.2
q3	139998.3
max	173577.7
average	133301.1

Table 3: Statistics of Expected Value

Another method to summarize the expected value, is to use the Bestfit program. The expected value has a weibull distribution with a mean of 133 301 and a standard deviation of 12 025. For a confidence of 90%, the expected value will vary between 118 000 and 157 000 Rand per shift.

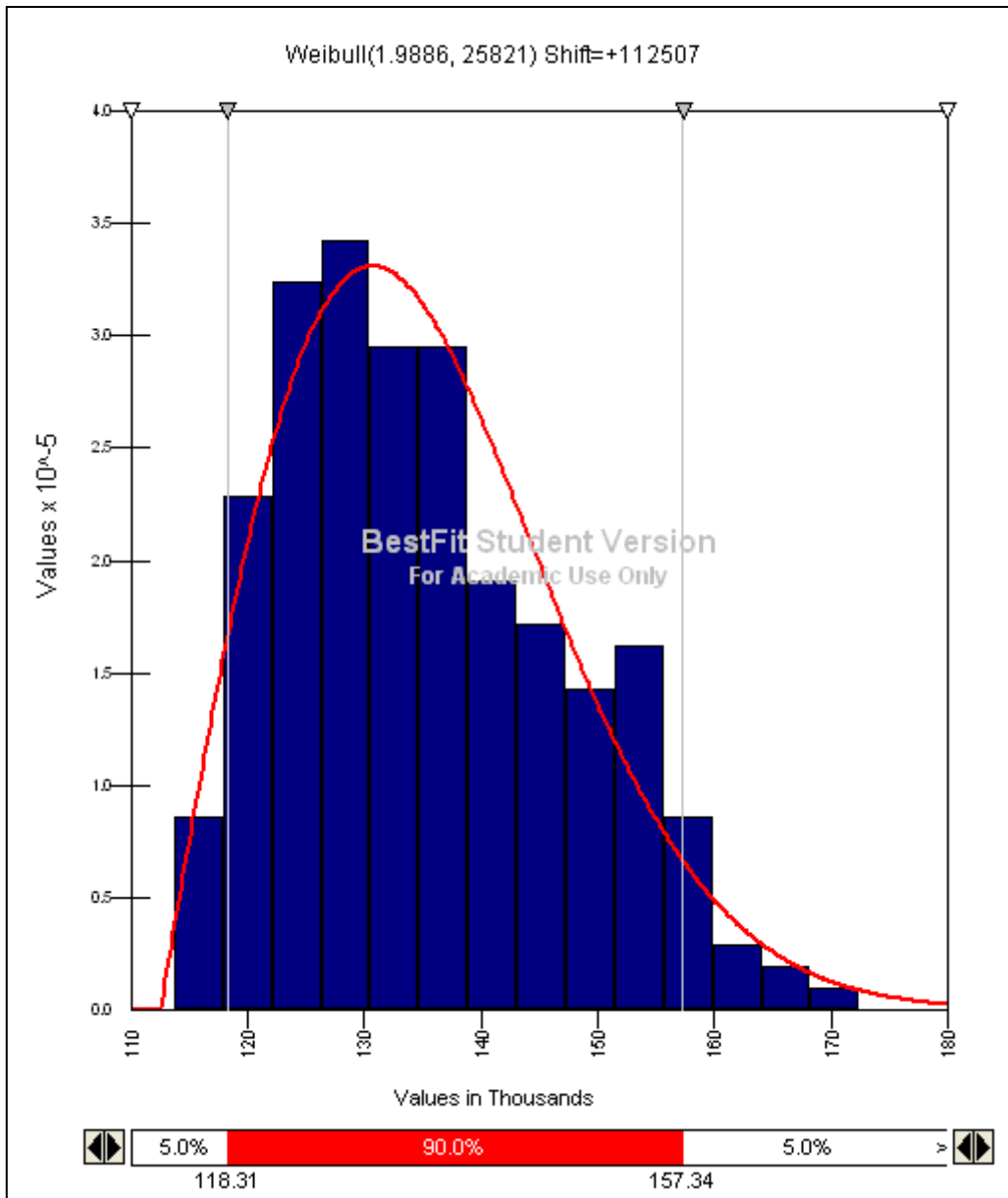


Figure 43: Distribution of Expected value

4.1.2.2 Potential Production Loss Due to an Unforeseen Dyke

This diagram is a summary of different scenarios that can occur and their potential production losses. It applies to scenarios that may occur with or without the presence of burnt coal, with pit room available, with reference to varying thickness of the dykes. The scenarios include the following:

- In the case of a 1m dyke with burnt coal, the approximate production loss is 4500 tons of coal.

- In the case of a 2m dyke with burnt coal, the approximate production loss is 9000 tons of coal
- In the case of a 5m dyke with burnt coal, the approximate production loss is 22500 tons of coal.
- In the case of a 1m dyke without burnt coal, the approximate production loss is 2250 tons of coal.
- In the case of a 2m dyke without burnt coal the approximate production loss is 4500 tons of coal.
- In the case of a 5m dyke without burnt coal, the approximate production loss is 11250 tons of coal
- In the case where no pit room is available, the approximate production loss is 750 tons of coal.

	No Pit Room Available						Pit Room Available
	With Burnt Coal			Without Burnt Coal			
	1m	2m	5m	1m	2m	5m	
Loss of shifts	6	12	30	3	6	15	0.5
Tons loss per shift	750	750	750	750	750	750	1500
Total Tons loss	4500	9000	22500	2250	4500	11250	750
Average loss of Tons	7821.429						

Table 4: Scenarios of Unforeseen Dyke

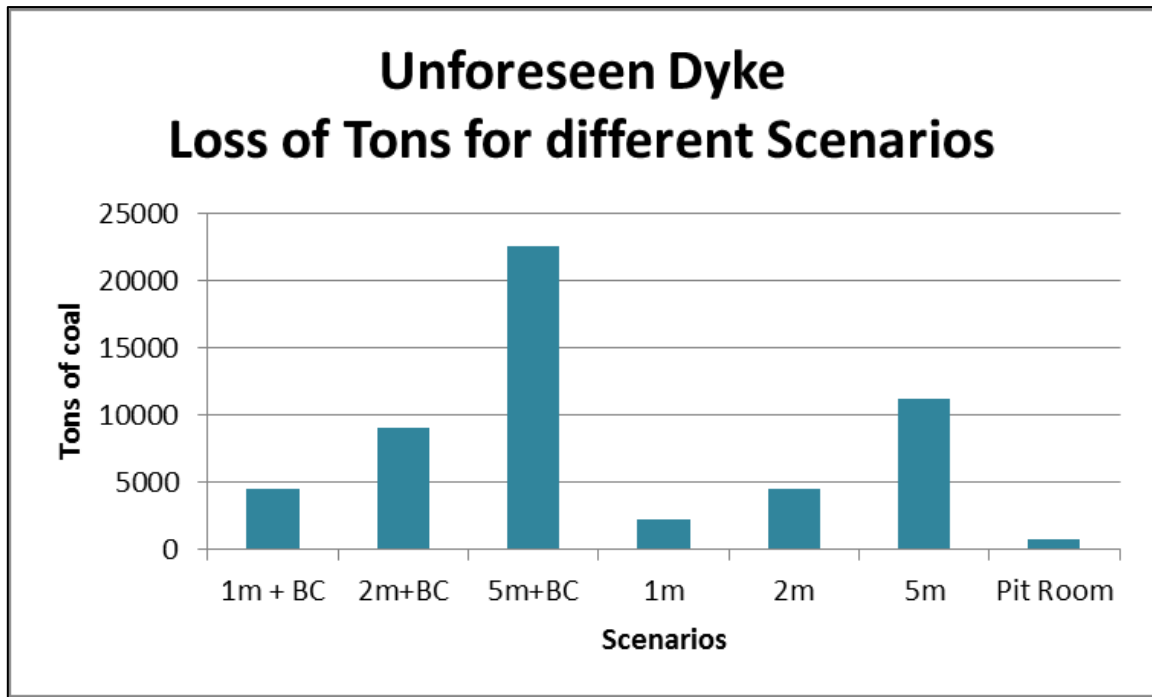


Figure 44: Graph of Unforeseen Dyke Loss of Tons for Different Scenarios

4.2 Evaluation

The flow chart below indicates the progression to the model verification and validation phase. The subsequent section elaborates on the verification and validation phase.

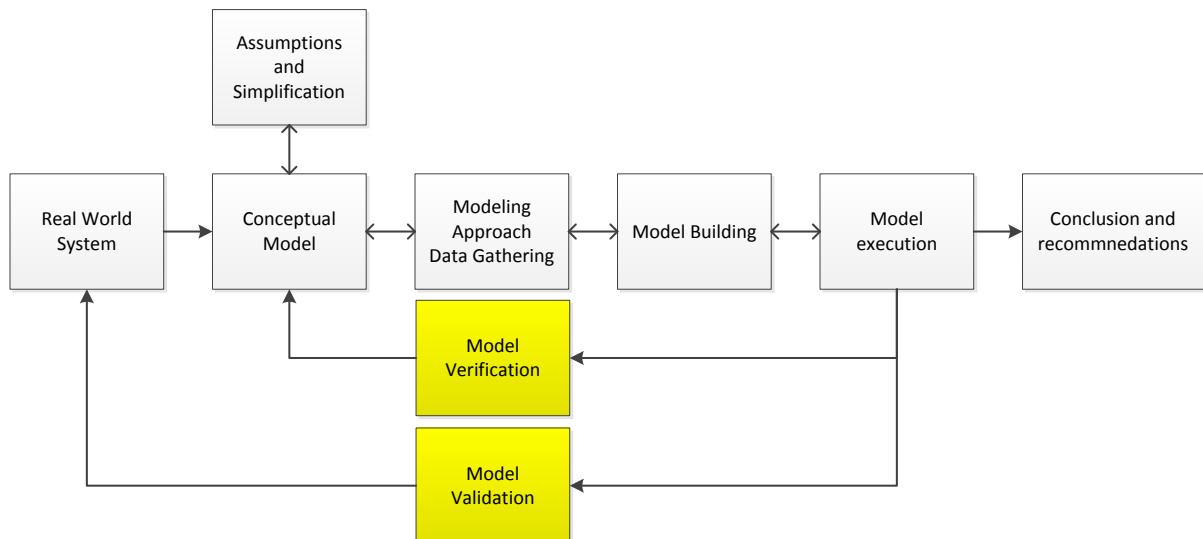


Figure 45: General Model Approach - Model Verification and Validation (Kruger, 2013)

Evaluation is a critical part of building a model. It ensures that the model and results are representative of the real world system. As for this project, evaluation was applied by verifying and validating the model.

In order to verify the model, debugging was done. The debugging included checking and evaluating all figures and amounts through all the stages of the project. The Excel calculations and the Monte Carlo simulation were also checked and assessed by involved persons.

For validation of the model, the user and the programmer must both be satisfied with the results. Both parties must agree that the model is usable and acceptable. To test this statement a survey was compiled and given to the user to rate the usefulness of the model and its result. The surveys were sent to all the involving persons in the industry. (See appendix G) The surveys showed that the users were 92% satisfied with the result of the model. This value indicates that the model is validated and has a significant contribution to the industry.

4.3 Conclusion

The flow chart below indicates the progression of the model to the conclusion and recommendation phase. The section below elaborates on the conclusions and recommendations.

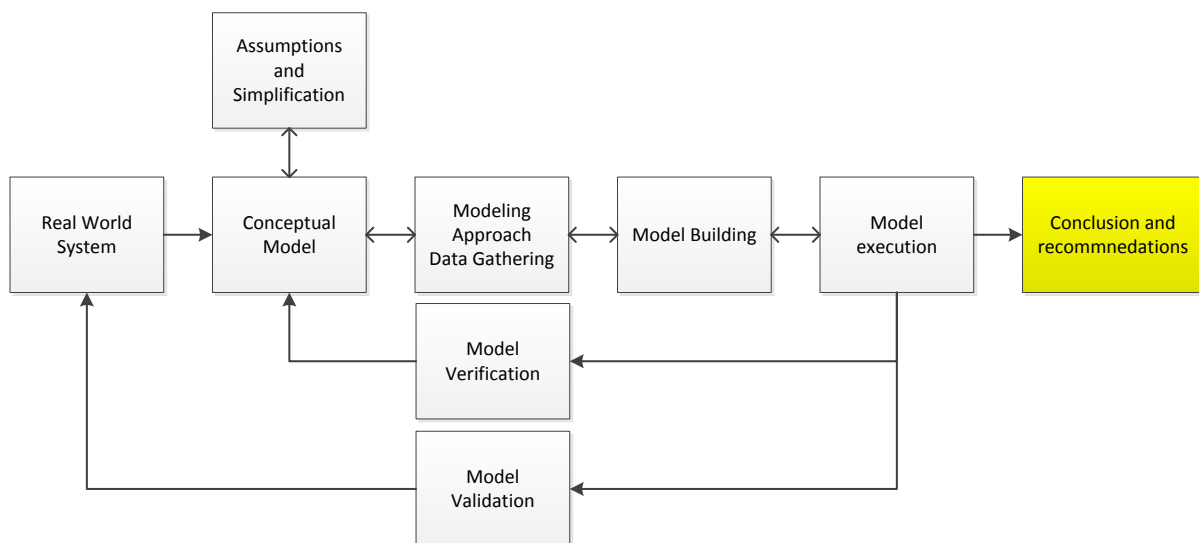


Figure 46: General Model Approach - Conclusion and Recommendations (Kruger, 2013)

In conclusion the value of R 65 million generated by the model indicates the risks to the process as a result of an unforeseen dyke or sill. This value refers to the maximum amount of drilling and not necessarily the total amount that should be spent. It now becomes a business decision to determine how much will be utilised to reduce the risk. This decision is based on economic requirements and the level of risk avoidance practised by the company. The funds can be allocated to different areas to obtain more perfect information and / or to optimise the production, stoneworks and geological exploration processes.

The company will benefit if they decide to invest in more drilling, because it will provide more perfect information on the dykes and sills. The increased drilling delivers the benefit of better planning. The better planning leads to reducing bottlenecks of the stoneworks process. For the reduction of bottlenecks, the stoneworks operations must be effective and efficient. As a result reduced bottlenecks are brought about by the combination of better planning and an effective and efficient stoneworks process. The better planning is enabled by perfect information. The formula below describes the above mentioned statements.

Reduce Bottlencks = f{better planning and effective and efficient stonework process}

Better planning = f{perfect information}

The actual amount of drilling is R8 million per year. This represents only 12% of the calculated risk and is the result of economic considerations and risk avoidance practices as mentioned above. The optimisation of this amount and the allocation thereof did not fall within the parameters of this project and is a good opportunity for further development and future projects.

4.4 Recommendation

This project has the potential to be developed further. Below is a list of possible future endeavours:

- The development of the decision tree model to become more dynamic. The model must capture the changes of every month.
- A more in depth study of the operational approach of the stoneworks process.

- The incorporation of time studies relating to the process in order to determine operational deficiencies.
- The optimization of the geological drilling process
- An investigation of the possibility of drilling more holes to reduce the risk of an unforeseen dyke.
- Optimising and the allocating the expected value of, R 65 million in different areas.

The diagram below illustrates the possible options where the 65 million Rand can be spent. The money can be applied in one of the options or in both, depending on the business' decision. Firstly the amount can be used to obtain more perfect information, in other words to drill more vertical and horizontal holes. The second option is to optimize the current processes with the money. These processes include: the production process, the stoneworks process and the geological process.

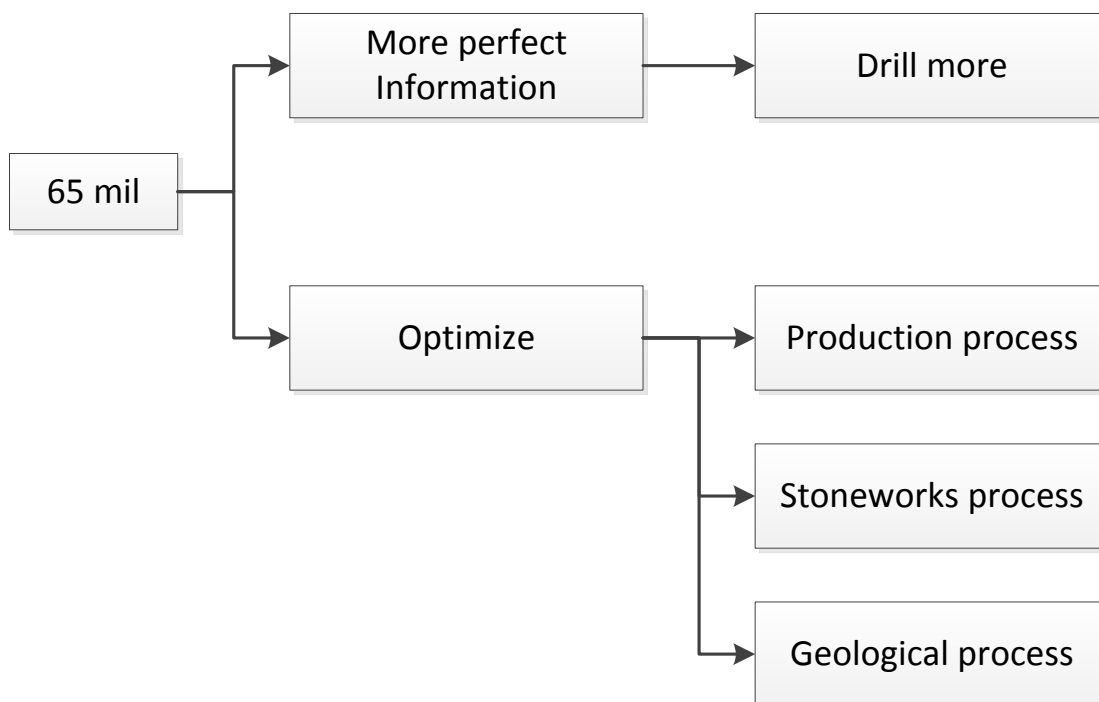


Figure 47: Project Recommendation

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Appendix A: Industry Sponsorship Form

Department of Industrial & Systems Engineering Final Year Projects

Identification and Responsibility of Project Sponsors

All Final Year Projects are published by the University of Pretoria on *UPSpace* and thus freely available on the Internet. These publications portray the quality of education at the University and have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide the best guidance to the student on the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will be considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

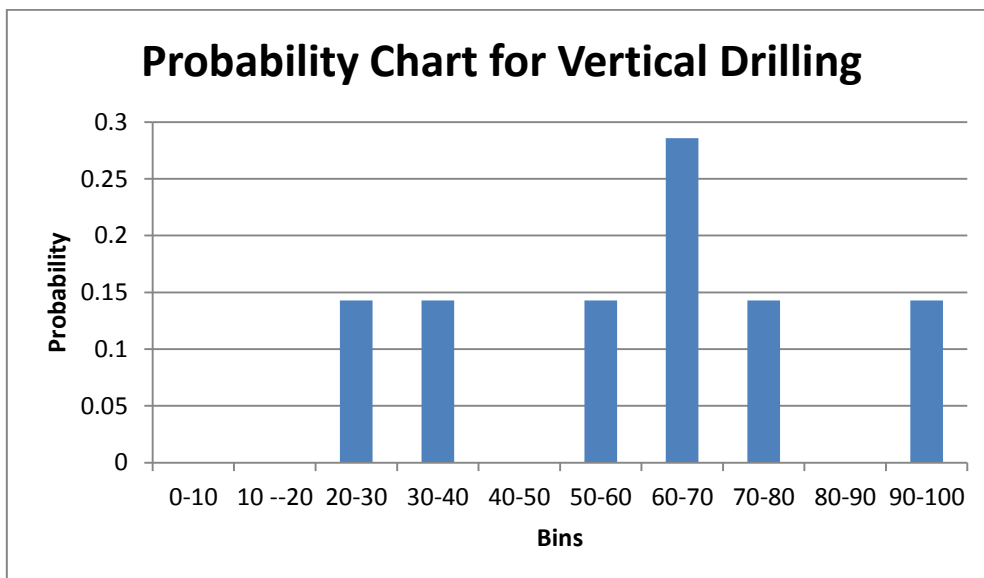
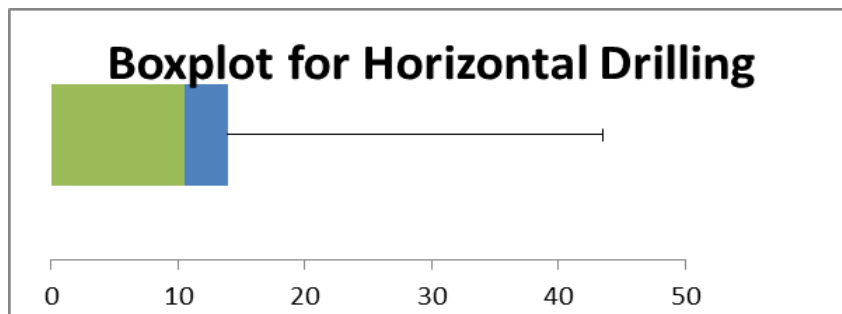
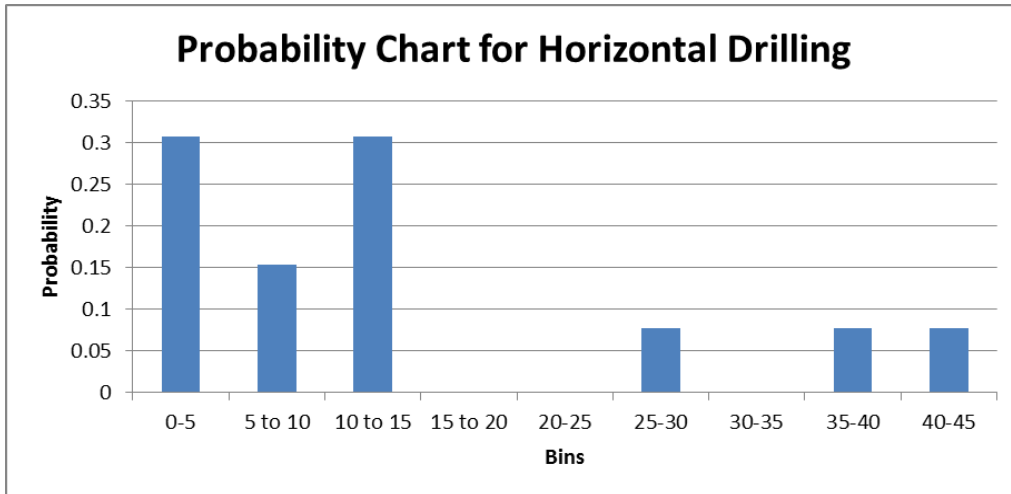
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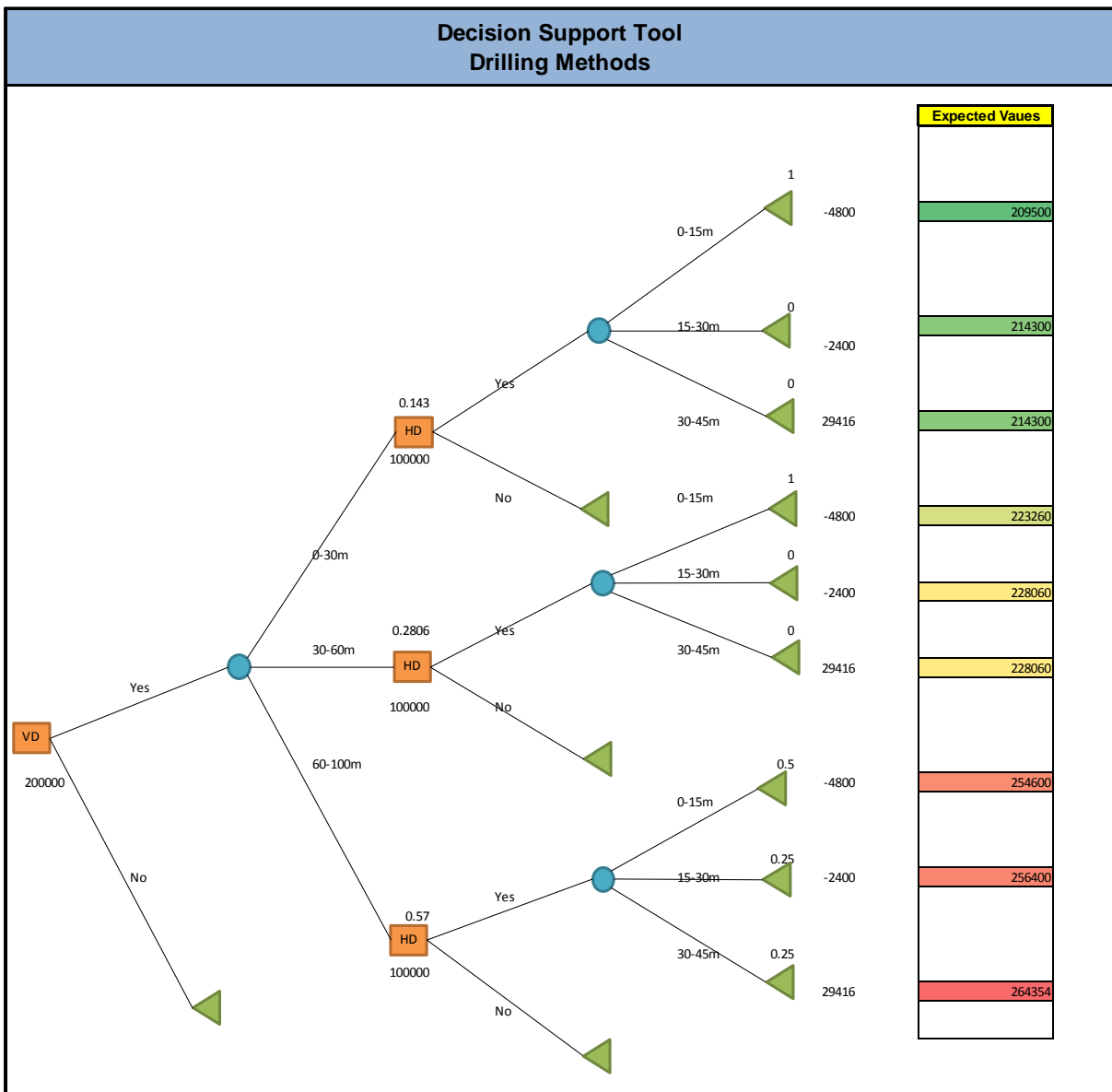
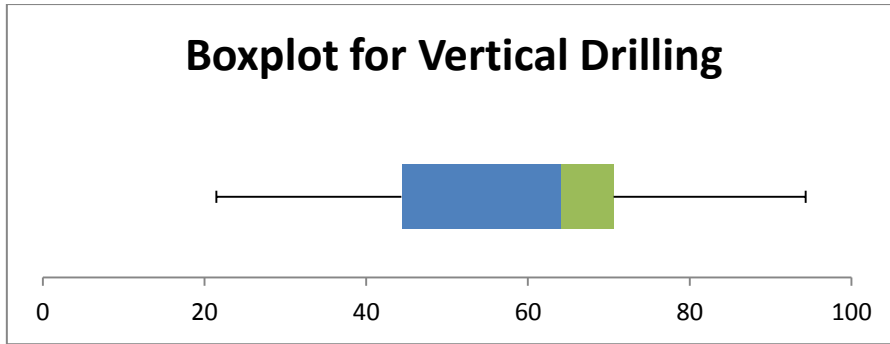
Company:	Sasol Wynboon
Project Description:	THE STONEWORK PROCESS AS AN INTEGRAL PART TO MEET PRODUCTION REQUIREMENTS
Student Name:	L. DOWLING
Student number:	29049131
Student Signature:	<i>Dowling</i>
Sponsor Name:	Gerrit Koke
Designation:	Shift manager
E-mail:	gerrit.koke@sasol.com
Tel No:	017 614 8607
Cell No:	082 306 7644
Fax No:	011 522 8876
Sponsor Signature:	<i>[Signature]</i>

Appendix B: Geological Data Analysis and Probability Tree

	Vertical		Horizontal		Actual		VD (m)	HD (m)	Structure
	x	y	x	y	x	y			
1	2981.03	-2943199.26	2958.06	-2943192.81	2945.16	-2943187.57	37.73	13.92	Sill
2	4111.9	-2944753.96	4117.63	-2944795.5	4111.91	-2944804.91	50.95	11.01	Sill
3	3829.53	-2946538.68	3728.31	-2946559.68	3757.93	-2946559.68	74.62	29.62	Sill
4	5866.25	-2941705.76	5890.43	-2941651.71	5894.87	-2941645.66	66.57	7.50	Sill
5	8315.97	-2952398.12	8293.4	-2952419.9	8255.11	-2952417.88	63.99	38.34	Sill
6	11687.1	-2953727.22	11756.2	-2953791.44	11756.2	-2953791.44	94.36	0.00	Sill
7			12953.48	-2949741.28	12953.48	-2949741.28		0.00	Dyke
8			4872.42	-2943187.92	4863.96	-2943194.37		10.64	Dyke
9	8333.55	-2951689.11	8342.3	-2951695.79	8351.51	-2951700.86	21.46	10.51	Sill
10			7478.98	-2949576.27	7478.98	-2949576.27		0.00	Dyke
11			9920.52	-2951806.2	9891.6	-2951773.73		43.48	Dyke
12			3401.4	-2942933.52	3397.71	-2942926.6		7.84	Dyke
13			8546.63	-2951041.08	8546.63	-2951041.08		0.00	Dyke

VD		HD		
0-30	1	0-15	1	100
	0.14	15-30		
		30-45		
30-60	2	0-15	2	100
	0.285714	15-30		
		30-45		
60-100	4	0-15	2	50
	0.571429	15-30	1	25
		30-45	1	25





Appendix C: Dyke Statistics

Dyke Statistics for the input to the decision tree

	Name	Burnt Coal Present	Burnt Coal Before	Dyke size	Burnt Coal After	Sum
1	C	Yes	7	4	11	22
2	B	Yes	15	2	20	37
3	B1	Yes	33	2	63	98
4	B2	No		1		1
5	C1	Yes	2	1	2	5
6	Z	Yes	0.5	1	0.5	2
7	Z1	No		2.5		2.5
8	C2	Yes	80	4	20	104
9	E	No		6		6
10	J1	No		0.8		0.8
11	J2	No		0.8		0.8
12	J3	No		0.5		0.5
13	F	No		2.5		2.5
14	G	Yes	5	6	11	22
15	N	No		3		3
16	Y	Yes	6	3.5	6	15.5
17	X	Yes	5	2.5	5	12.5
18	L1	Yes	11	4	11	26
19	W	No		1.5		1.5
20	U	No		1.4		1.4

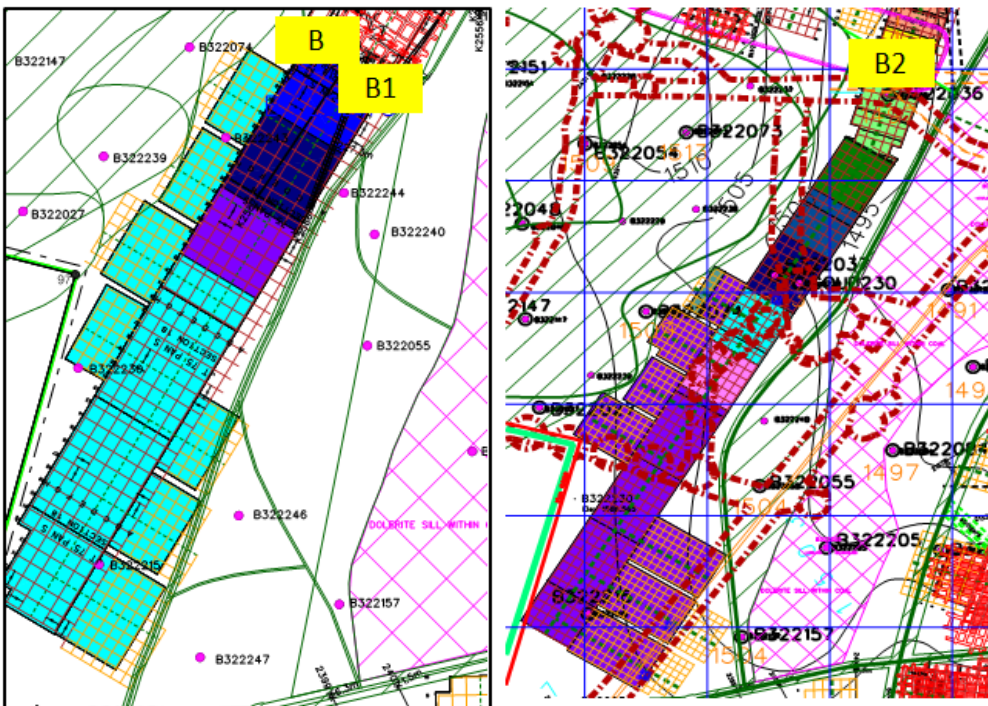
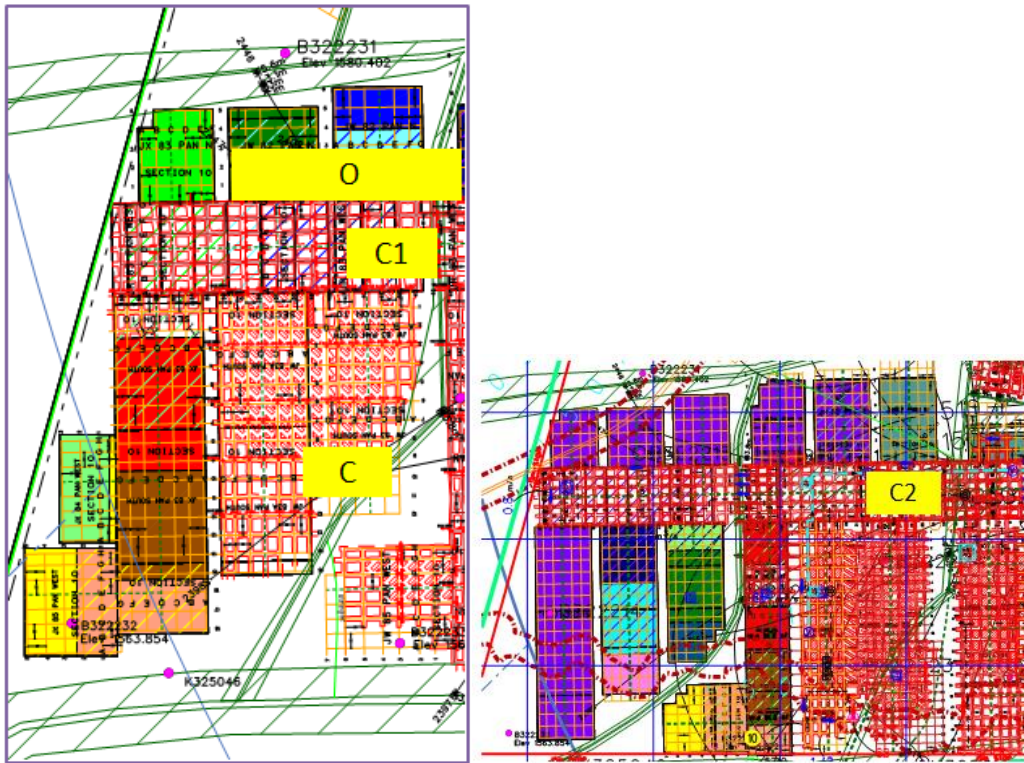
No Burnt Coal

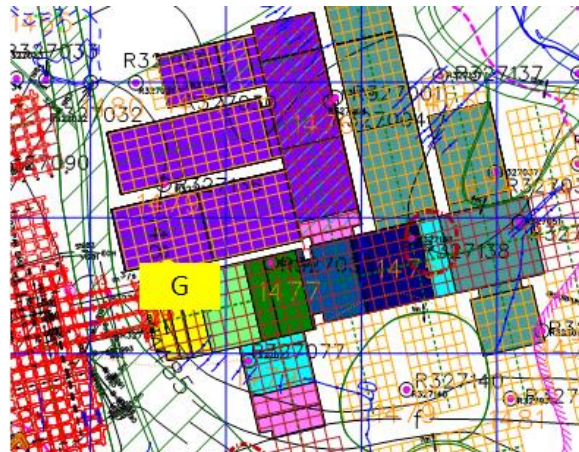
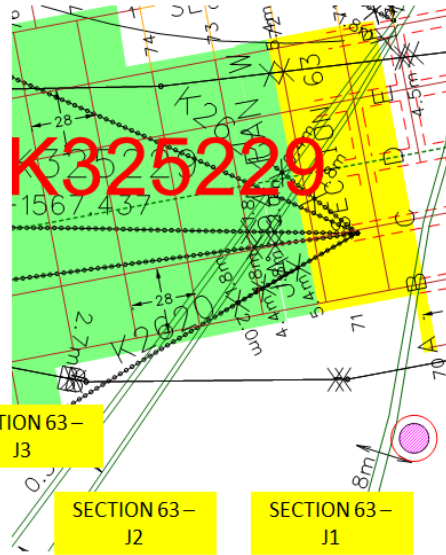
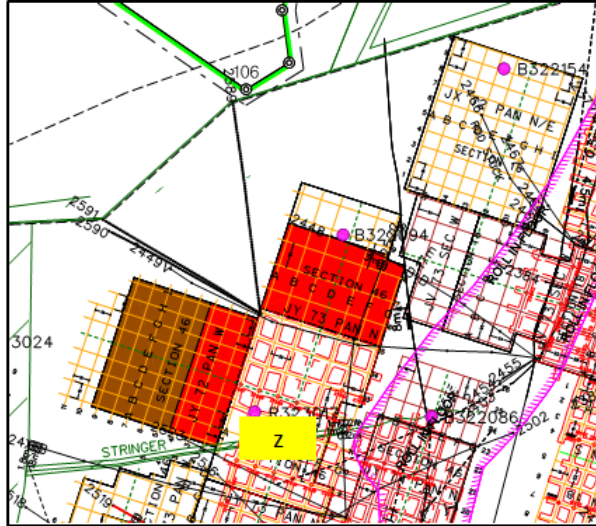
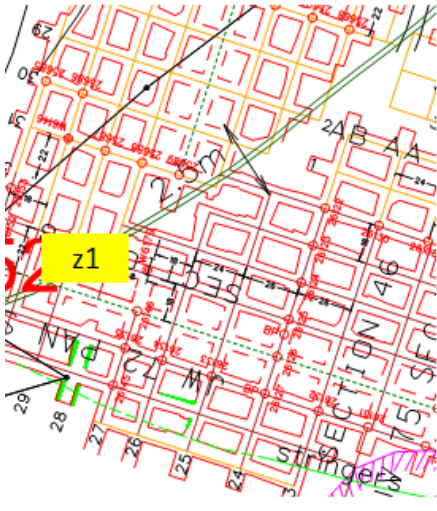
Bin	Frequency	Probability
0--1	4	0.4
1--3	4	0.4
3--6	2	0.2
	10	

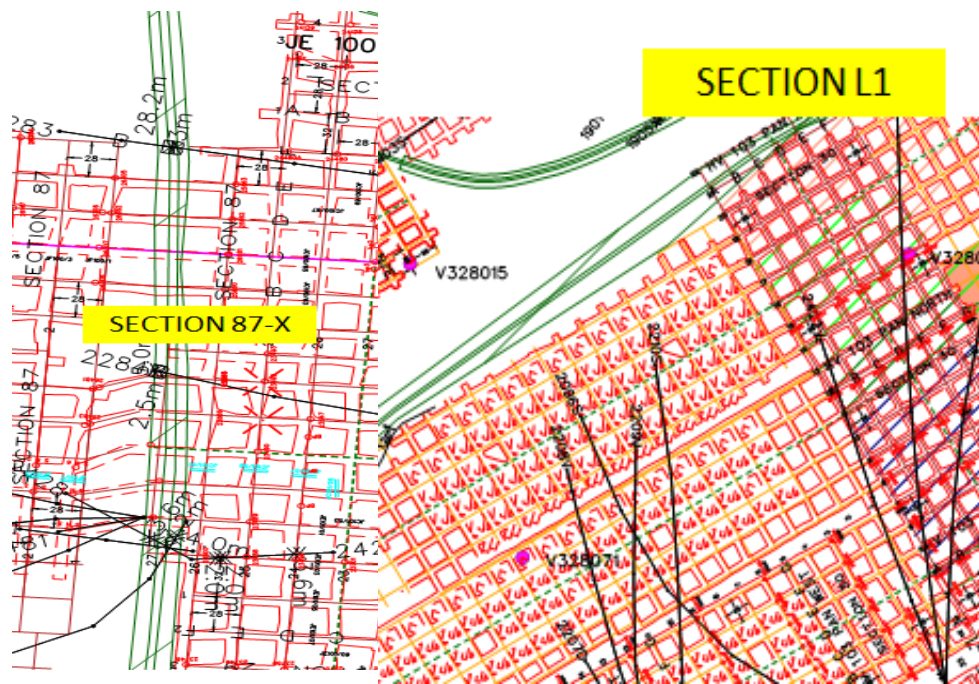
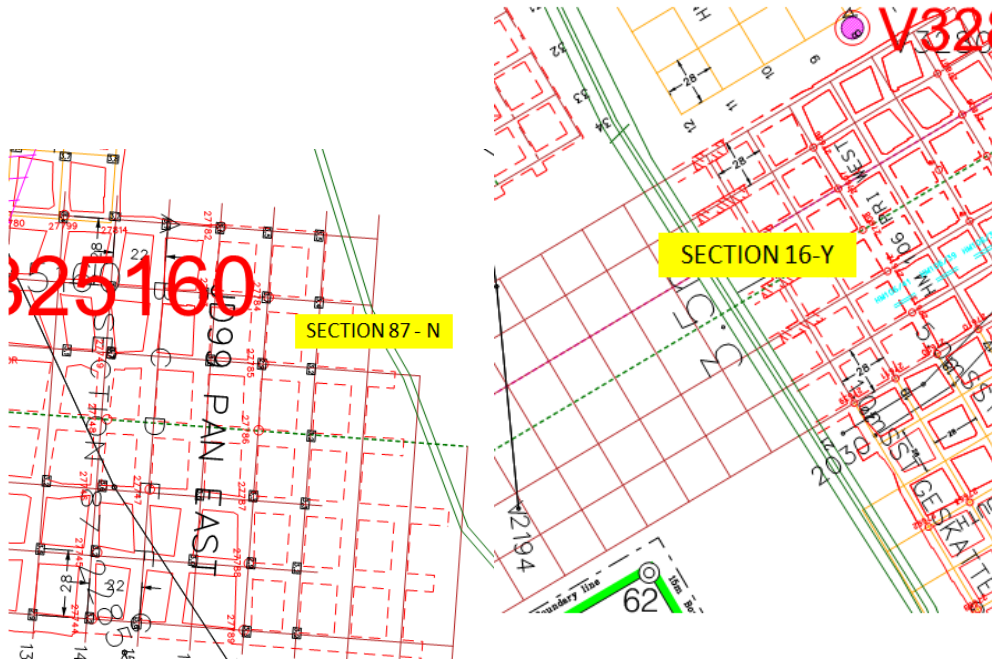
Burnt Coal

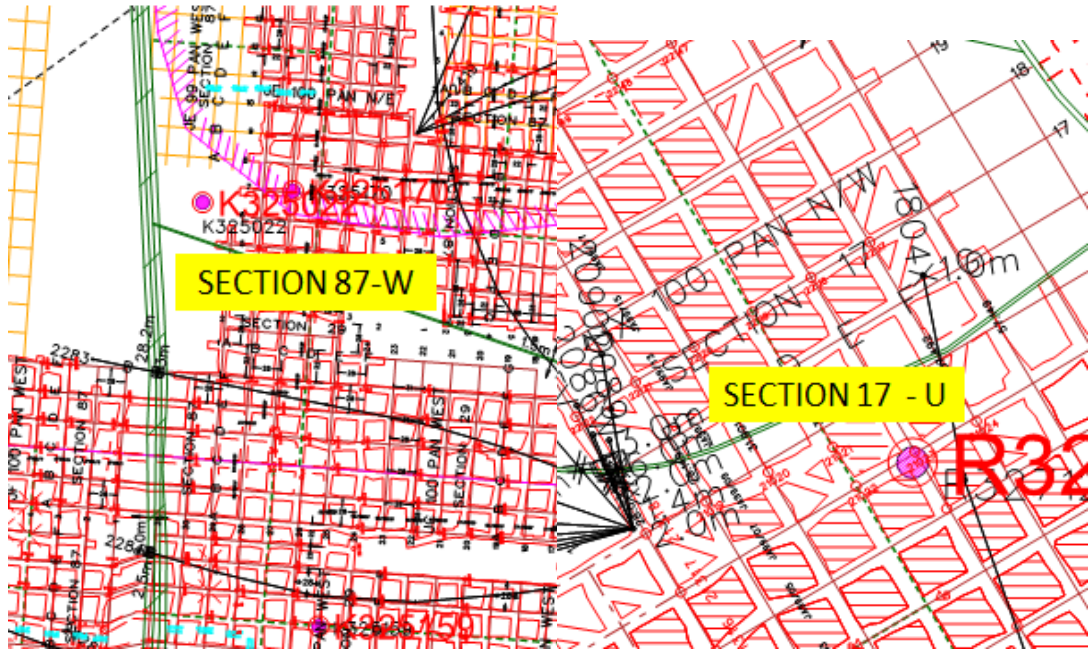
Bin	Frequency	Probability
0--1	2	0.2
1--3	3	0.3
3--6	5	0.5
	10	

The diagrams below depict the dykes that were used for the analysis:







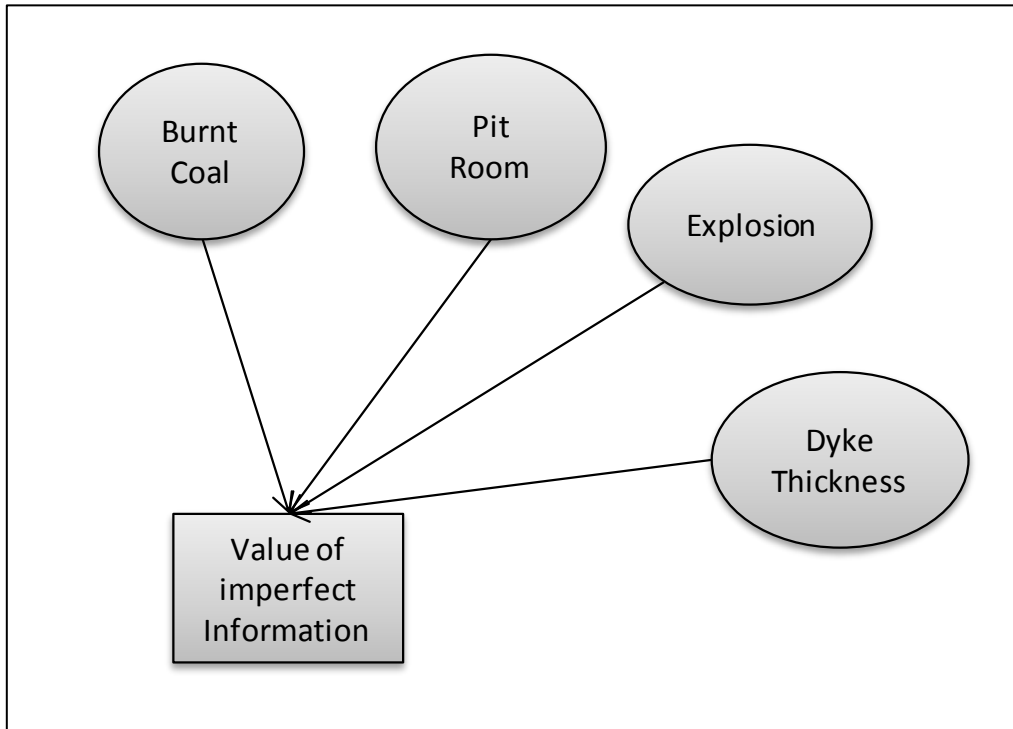


Appendix D: Input Data to Decision Tree

Variables		Calculations	Min (-10%)	Most Likely	Max (=10%)	Triangular constant	Triangular Random	
Burnt Coal	Yes Prob	x1	0.5	0.45	0.5	0.55	0.458355813	
	No Prob	x2	0.5	0.45	0.5	0.55	0.488373558	
Explosion	Yes Prob	x3	2.6936E-06	2.42424E-06	2.6936E-06	2.96296E-06	0.5	2.75137E-06
	No Prob	x4	0.999997306	0.899997576	0.999997306	1	0.999973065	0.952811056
	Payoff	x5	40,800,000.00	36720000	40800000	44880000	0.5	39380789.13
Pitroom	Yes Prob	x6	0.953703704	0.858333333	0.953703704	1	0.673202614	0.971671719
	Payoff	x7	97500	87750	97500	107250	0.5	98773.86356
	No Prob	x8	0.046296296	0.041666667	0.046296296	0.050925926	0.5	0.047695196
Thickness	1m + BC Prob	x9	0.2	0.18	0.2	0.22	0.5	0.207788679
	Payoff	x10	292500	263250	292500	321750	0.5	303346.4178
	2m+BC Prob	x11	0.3	0.27	0.3	0.33	0.5	0.297097304
	Payoff	x12	585000	526500	585000	643500	0.5	564750.4789
	5m+BC Prob	x13	0.5	0.45	0.5	0.55	0.5	0.486650069
	Payoff	x14	1462500	1316250	1462500	1608750	0.5	1475373.251
Pitroom	Yes Prob	x15	0.953703704	0.858333333	0.953703704	1	0.673202614	0.969525236
	Payoff	x16	97500	87750	97500	107250	0.5	101909.6524
	No Prob	x17	0.046296296	0.041666667	0.046296296	0.050925926	0.5	0.045133796
Thickness	payoff	x18	146250	131625	146250	160875	0.5	145010.2667
	1m Prob	x19	0.4	0.36	0.4	0.44	0.5	0.397686721
	Payoff	x20	292500	263250	292500	321750	0.5	295384.6311
	2m Prob	x21	0.4	0.36	0.4	0.44	0.5	0.401744354
	Payoff	x22	731250	658125	731250	804375	0.5	718786.1125
	5m Prob	x23	0.2	0.18	0.2	0.22	0.5	0.195079378

Appendix E: Influence Diagram

The diagram below illustrates the influences on the value of imperfect information:



Appendix F: Monte Carlo Simulation

The diagrams below are screenshots of the first 36 simulations in the Monte Carlo simulation.

correl	0.079990104	-0.079990104	0.020521732	-0.02052173	0.001699367	-0.942844072	0.130621393	0.942844072	-0.02335	0.00673019	
Expected Value	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	
0	159,142.37	0.508428662	0.491571338	2.77276E-06	0.999997227	4336715657	0.889570675	97457.41818	0.110429325	0.206908	306890.9154
1	128694.1364	0.496142968	0.503857032	2.74057E-06	0.999997259	4608090172	0.967605874	94729.92647	0.032394126	0.197987	305427.688
2	151260.6531	0.519425668	0.480574332	2.58709E-06	0.999997413	4438790607	0.917473118	100953.744	0.082526882	0.206282	288588.5746
3	142179.0691	0.487201495	0.512798505	2.64774E-06	0.999997352	4378687101	0.926667916	98179.45103	0.073332084	0.191972	289745.9912
4	137508.5348	0.465921767	0.534078233	2.66854E-06	0.999997331	4340364280	0.93461235	98464.79447	0.06538765	0.195079	290798.7965
5	131679.9715	0.483058195	0.516941805	2.66761E-06	0.999997332	4424234065	0.955901817	99488.97995	0.044098183	0.211921	284602.6154
6	138930.3241	0.479443836	0.520556164	2.74941E-06	0.999997251	4597009681	0.932920082	104213.543	0.067079918	0.200439	287222.9737
7	135536.9462	0.498066567	0.501933433	2.57864E-06	0.999997421	4424413838	0.956437341	105960.1572	0.043562659	0.194026	298902.3624
8	146007.2902	0.509699177	0.490300823	2.68388E-06	0.999997316	4117921369	0.920241706	99462.042	0.079758294	0.206355	303299.7968
9	145888.675	0.48577682	0.51422318	2.71917E-06	0.999997281	4492006491	0.924480506	100637.2119	0.075519494	0.216874	281208.6274
10	162023.7436	0.480503775	0.519496225	2.74014E-06	0.99999726	4121600307	0.872363224	94019.50869	0.127636776	0.217722	300090.2558
11	135391.3574	0.456547768	0.543452232	2.7785E-06	0.999997222	4356378762	0.929349719	98422.43648	0.070650281	0.207026	295512.7408
12	142670.1907	0.477369482	0.522630518	2.80018E-06	0.9999972	4452612633	0.904835583	96575.00264	0.095164417	0.192277	270825.2965
13	147391.2109	0.508119072	0.491880928	2.60499E-06	0.999997395	4379464462	0.928417874	106542.0666	0.071582126	0.205677	300864.8146
14	140593.1528	0.506400823	0.493599177	2.65926E-06	0.999997341	4559348655	0.949285743	101051.0057	0.050714257	0.191734	297087.7371
15	147666.129	0.501264305	0.498735695	2.64822E-06	0.999997352	4658239855	0.920177733	99442.79774	0.079822267	0.194353	285853.3176
16	125245.4266	0.484953422	0.515046578	2.72146E-06	0.999997279	4789393071	0.959171775	95346.58596	0.040828225	0.201245	299146.9946
17	124282.733	0.50802726	0.49197274	2.66685E-06	0.999997333	4510390578	0.966640321	100538.7042	0.033359679	0.188512	300115.9609
18	138705.6134	0.503780809	0.496219191	2.62324E-06	0.999997377	4319053972	0.930515547	101402.974	0.069484453	0.205022	280728.258
19	135758.9365	0.501042307	0.498957693	2.64817E-06	0.999997352	4371432700	0.938872488	101189.3954	0.061127512	0.207743	289704.8834
20	140555.2823	0.48005397	0.51994603	2.61516E-06	0.999997385	4654101756	0.919692954	97533.06874	0.080307046	0.20089	292644.2112
21	129020.6606	0.489663445	0.510336555	2.68183E-06	0.999997318	4603052153	0.965930216	98694.72211	0.034069784	0.197174	290709.265
22	137444.715	0.53187512	0.46812488	2.66521E-06	0.999997335	4258998755	0.940095038	98621.212	0.059904962	0.189587	294300.3493
23	160196.2899	0.498054937	0.501945063	2.50367E-06	0.999997496	4592916701	0.89637858	98694.87602	0.10362142	0.207803	293829.1746
24	147282.6036	0.527882841	0.472117159	2.55783E-06	0.999997442	4544723543	0.914718088	102514.3402	0.085281912	0.192545	276585.0363
25	134663.3067	0.480430805	0.519569195	2.78075E-06	0.999997219	4868142646	0.936918089	95192.41732	0.063081911	0.201174	291233.9974
26	166639.2274	0.496446862	0.503553138	2.73902E-06	0.999997261	4523656668	0.866662728	100118.3439	0.133337272	0.199993	292737.8116
27	121532.859	0.487389121	0.512610879	2.634E-06	0.999997366	4612463747	0.974271318	99778.82397	0.025728682	0.201858	304546.7655
28	141381.7155	0.512029513	0.487970487	2.60482E-06	0.999997395	4404796093	0.922256639	97208.8176	0.077743361	0.211008	295891.0408
29	125037.428	0.486294534	0.513705466	2.695E-06	0.999997305	4322444077	0.956546468	97395.79172	0.043453532	0.204007	302551.2855
30	139592.2193	0.50777201	0.49222799	2.58633E-06	0.999997414	4670174170	0.921734587	93732.42601	0.078265413	0.201417	309305.9309
31	127200.6607	0.511921157	0.488078843	2.56175E-06	0.999997438	4524746469	0.95838708	97677.57406	0.04161292	0.202037	280614.5741
32	119136.5814	0.518626554	0.481373446	2.62204E-06	0.999997378	4823084098	0.987062397	98027.33813	0.012937603	0.195332	290410.3965
33	133359.7705	0.531143685	0.468856315	2.78275E-06	0.999997217	4341485814	0.953365773	97855.93045	0.046634227	0.19862	290491.0563
34	132103.5494	0.497722574	0.502277426	2.73939E-06	0.999997261	4327335692	0.948733729	99875.93927	0.051266271	0.197591	282875.0207
35	140897.1047	0.499367046	0.500632954	2.70768E-06	0.999997292	4326258242	0.920799246	94844.61039	0.079200754	0.193176	281851.499
36	133150.4009	0.504688229	0.495311771	2.64252E-06	0.999997357	4568733306	0.945723137	98935.21064	0.054276863	0.202664	293795.2767
36	145102.1969	0.494388679	0.505611321	2.63982E-06	0.99999736	4315163873	0.908349765	99986.04464	0.091650235	0.197432	294322.0666

-0.02457	0.015094	0.033253902	0.073887522	-0.24046	0.154247	0.240461392	-0.00587	0.006149	0.001256	-0.00231	0.020545	-0.00275
x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21	x22	x23
0.309944	586522.3	0.483147265	1509788.862	0.939023	95517.46	0.060976591	149523.1	0.395	289261.7	0.38585	763775	0.219149
0.286019	584056.3	0.515994695	1441906.354	0.892479	97807.12	0.107520585	144278.1	0.416181	290153.6	0.36702	709452.5	0.216799
0.319717	580908	0.474000817	1536428.301	0.949598	103282.4	0.050401781	150884.1	0.3851	299516.6	0.387785	745300.5	0.227114
0.292467	599353.9	0.515560256	1537907.645	0.935644	94683.69	0.064355919	141200	0.412228	287349.2	0.39079	703291.6	0.196982
0.29175	558988.9	0.513170997	1502180.027	0.945163	98817.76	0.054836678	141684.1	0.40785	309932.3	0.404628	692964.3	0.187521
0.285009	597926.6	0.503069893	1467110.683	0.932083	102023.9	0.067916538	140894.3	0.410197	268399.7	0.402283	671960.5	0.18752
0.299673	608709.2	0.499888895	1542512.917	0.963395	95787.8	0.036605279	146614.8	0.429184	283761.8	0.414847	760769.2	0.155969
0.285975	580756.7	0.519998726	1530257.473	0.921284	96801.01	0.078715818	140026.1	0.388673	277026.2	0.395228	704182	0.216099
0.310731	584499.1	0.482914289	1464765.379	0.952778	101355.9	0.047221948	143236	0.405021	301745	0.398063	782131.8	0.196916
0.310301	606315.5	0.47282425	1420459.259	0.909303	97510.9	0.090696594	150359.2	0.405143	294265.8	0.38878	750202.7	0.206078
0.297077	567710	0.485201199	1516777.302	0.955152	101289.9	0.044848433	149339.1	0.402284	281107.9	0.398262	738759.5	0.199454
0.294863	602477.4	0.498110683	1488076.002	0.969466	97484.38	0.030534405	149326.8	0.428006	278800.5	0.385696	740189.9	0.186298
0.297841	576088	0.509881558	1436823.95	0.980509	93812.48	0.019491449	145064.5	0.369241	296590.3	0.412843	763747.1	0.217916
0.305318	559711.5	0.489004807	1476407.86	0.935741	100004.4	0.064258548	142859.2	0.393438	286882.2	0.385559	759527.2	0.221003
0.300112	623720.6	0.508154749	1437427.114	0.894143	100162.2	0.105856957	150941.6	0.411888	294164.4	0.406119	751925.9	0.181992
0.290318	606952.3	0.515329446	1380001.276	0.926687	100395	0.07331345	141436.8	0.422486	283164.1	0.389531	766526.3	0.187982
0.301127	567039.2	0.49762767	1592154.667	0.962415	97211.98	0.037585143	143472.1	0.393466	289137.4	0.412276	725021.7	0.194258
0.288732	574780.6	0.522756364	1508199.63	0.953743	95202.77	0.046256932	139162.8	0.410255	303575.4	0.402788	684850.9	0.186957
0.296844	594581.6	0.498133584	1451912.015	0.966062	97337.23	0.033937873	151142.5	0.41763	305919.7	0.400713	707278.9	0.181657
0.309806	606799.6	0.482450608	1393561.84	0.949734	96990.44	0.050266337	143480.5	0.388659	281957.3	0.385214	719584	0.226127
0.292702	577095.1	0.506408297	1435474.751	0.973821	99709.49	0.02617859	148819.2	0.400666	290689.7	0.389321	703173.7	0.210013
0.296227	600070.7	0.506598984	1483337.806	0.922319	100128.9	0.077681439	151891.5	0.403053	289847	0.388723	704288.5	0.208224
0.310856	608790.9	0.499556711	1478228.338	0.958821	99751.48	0.04117913	151971.7	0.413067	299081.7	0.3931	671661.7	0.193833
0.29789	575952.1	0.494307107	1525899.127	0.919539	99457.36	0.08046074	146632.2	0.39044	303362.2	0.390646	731918.3	0.218914
0.287836	581095.3	0.519618466	1463036.48	0.970296	93946.85	0.029704246	158435.4	0.409006	296151	0.404315	714260	0.186679
0.303954	591779.4	0.494871824	1436630.629	0.947084	96596.31	0.052915889	147859.6	0.406256	294568.6	0.394481	759190.3	0.199263
0.310849	581758.1	0.489158178	1438558.418	0.9418	95229	0.058200369	142755.8	0.402239	309518.3	0.37672	729221.6	0.221041
0.306557	569962.2	0.491585069	1339160.228	0.938962	97868.67	0.061037918	143189.3	0.41107	298499.3	0.395465	722434.8	0.193465
0.313361	558935.8	0.475631057	1411750.188	0.951116	98452.99	0.048840001	146737.3	0.387009	289025.6	0.395515	702793.5	0.217476
0.29923	611552.5	0.496762924	1406089.808	0.967548	98595.41	0.032452426	143747.1	0.407832	287729.2	0.416037	735068.8	0.176131
0.310565	602738	0.488018374	1436835.863	0.963116	97247.83	0.036884255	144877.3	0.413647	290368.4	0.405764	755954.4	0.180589
0.315394	597549.1	0.482569071	1411558.801	0.933931	96732.99	0.066068882	148070.2	0.432537	282182.8	0.40021	706490.6	0.167253
0.305458	573809	0.499209838	1487705.349	0.924548	99520.15	0.075452163	148498.5	0.399519	300753.9	0.407448	707301.8	0.193033
0.292964	573062.2	0.508415694	1487399.676	0.931967	96205.75	0.068033437	150936.4	0.381215	307795	0.380662	719101.4	0.238124
0.308235	582560.7	0.494174247	1529724.588	0.959633	98987.58	0.040367375	143917.4	0.437383	316508.8	0.418369	708129	0.144248
0.310706	585462.9	0.496117795	1470448.876	0.940536	93697.33	0.059463576	144933.4	0.421295	290497.7	0.406193	737413.1	0.172512
0.30711	571455.1	0.49022659	1531172.743	0.922745	89203.99	0.077255407	143829.6	0.423442	295928.6	0.388913	742473.6	0.187644
0.309031	564416.2	0.493536645	1413066.668	0.959978	94823.07	0.040219969	145604.6	0.416013	309240.7	0.4122	742525.8	0.171787

Appendix G: Surveys

The surveys collected for the evaluation stage of the project is compiled in the following appendix.

User Satisfaction Survey

Project Description:

The value of imperfect information is reflected in the uncertainty of an unforeseen dyke. A decision tree model was built with the possibilities and probabilities of actual events in the past to determine the value of imperfect information. A Monte Carlo simulation was computed using triangular distribution for the input variables. A sensitivity analysis was performed to determine the input values with the highest impact on the expected value of R 65 million. From the analysis it was clear that the expected value is most sensitive to the **availability of pit room.**

The value of R 65 million generated by the model indicates the risks to the process as a result of an unforeseen dyke or sill. It now becomes a business decision on how much will be utilised to reduce the risk. This decision is based on economic requirements and the level of risk avoidance practised by the company. The funds can be allocated to different areas to obtain more perfect information and / or to optimise the production, stoneworks and geological exploration processes.

User name:	Reghardt van der Merwe
Designation:	Business planning Manager

Rate the student against the 4 criteria from 1 to 4. Mark with "x" in the box below:

Indicators			
1	2	3	4
Not useful	Somewhat useful	useful	Very useful

Criteria	Grade			
	1	2	3	4
The value generated by the model is useful to the user			X	

The student showed much enthusiasm; with the necessary experience in future she will be of great help to reduce risk in this regard. Good luck with your final exams and assessments!
RvdM

User Satisfaction Survey

Project Description:

The value of imperfect information is reflected in the uncertainty of an unforeseen dyke. A decision tree model was built with the possibilities and probabilities of actual events in the past to determine the value of imperfect information. A Monte Carlo simulation was computed using triangular distribution for the input variables. A sensitivity analysis was performed to determine the input values with the highest impact on the expected value of R 65 million. From the analysis it was clear that the expected value is most sensitive to the availability of a pit room.

The value of R 65 million generated by the model indicates the risks to the process as a result of an unforeseen dyke or sill. It now becomes a business decision on how much will be utilised to reduce the risk. This decision is based on economic requirements and the level of risk avoidance practised by the company. The funds can be allocated to different areas to obtain more perfect information and / or to optimise the production, stoneworks and geological exploration processes.

User name:	Cornelius Zwaan
Designation:	Mine Planner

Rate the student against the 4 criteria from 1 to 4. Mark with "x" in the box below:

Indicators			
1	2	3	4
Not useful	Somewhat useful	useful	Very useful

Criteria	Grade			
	1	2	3	4
The value generated by the model is useful to the user				*

User Satisfaction Survey

Project Description:

The value of imperfect information is reflected in the uncertainty of an unforeseen dyke. A decision tree model was built with the possibilities and probabilities of actual events in the past to determine the value of imperfect information. A Monte Carlo simulation was computed using triangular distribution for the input variables. A sensitivity analysis was performed to determine the input values with the highest impact on the expected value of R 65 million. From the analysis it was clear that the expected value is most sensitive to the availability of a pit room.

The value of R 65 million generated by the model indicates the risks to the process as a result of an unforeseen dyke or sill. It now becomes a business decision on how much will be utilised to reduce the risk. This decision is based on economic requirements and the level of risk avoidance practised by the company. The funds can be allocated to different areas to obtain more perfect information and / or to optimise the production, stoneworks and geological exploration processes.

User name:	Fabian Francis
Designation:	Chief Geologist

Rate the student against the 4 criteria from 1 to 4. Mark with "x" in the box below:

Indicators			
1	2	3	4
Not useful	Somewhat useful	useful	Very useful

Criteria	Grade			
	1	2	3	4
The value generated by the model is useful to the user				x