Integration of Fleet Production and Cost Analysis in Mine Design and Planning

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An investigation in the possibility to integrate fleet selection (through FPC) in the mine design process, allowing for the analysis of various potential haul road scenarios and from there being able to make a decision on an optimal fleet selection.

Master Thesis

By

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ABSTRACT

Haul road characteristics such as the width and grade dictate the maximum size of the equipment and impact the performance of the fleet that operates in an open pit mine. Besides this, the haul road characteristics have an influence on the pit geometries by affecting the stripping ratio, and thus the final mine design. Where the equipment size has an impact on production, and thus costs per ton, the stripping ratio illustrates the ratio of waste to ore. The combination of these impacts illustrates that the haul road design in combination with fleet selection can have a significant influence on a project's theoretical Net Present Value (NPV).

Currently, fleet selection is performed during one of the final stages of the mine design process, where haul road characteristics have already been determined and integrated. This leaves ample room for the consideration of alternative equipment- and fleet sizes, including the possibility of implementing Autonomous Haulage Systems (AHS). The purpose of this thesis is to determine if fleet selection can be integrated into an early stage of the mine design process, and thus a more optimal decision concerning haul road design and fleet selection can be realized. If different haul road characteristics and their related equipment fleets are considered at an earlier stage, it is possible to assess the impact of these aspects before the mine design is completed, leaving room for adjustments. This will help to identify a (more) optimal economic scenario for the entire project.

This was investigated in a case study by assessing the impact, in terms of total tonnage, of different haul road characteristics on the mine designs of three gold deposits of different sizes. These gold deposits represent Greenfield projects and were constructed using tutorial data due to the scarcity of representational data. For this process, the mine design programs NPVScheduler and StudioOP from the company Datamine were used. Caterpillar's Fleet Production and Cost Analysis (FPC) tool was used to assess the appropriate fleet selection related to the haul road layouts, and investigate the economic impact of each scenario.

The outcomes of the case study indicate that fleet selection can take place at the step in the mine design process where benches and haul roads are designed. Because of the interaction between equipment size and haul road characteristics, a comparison of different scenarios at this stage makes it possible to identify the most optimal economic solution. However, since the options related to fleet selection and haul road design are strongly dependent on site-specific variables, it is considered unrealistic to come to a general, uniform approach regarding the problem statement.

Besides this, it can be concluded that a decrease in haul road width and an increase in grade has a significant positive impact on the stripping ratio, resulting in an increase of a project's theoretical NPV. This significance is shown to decrease as pit geometries increase. On the other hand, narrower haul roads are associated with smaller equipment, which generally results in a higher cost per ton. Autonomous Haulage Systems could offer solutions that reduce some of these negative aspects related to smaller equipment sizes, and additionally emphasize the positive aspects of a decrease in haul road width. In addition to this, recent literature has illustrated some significant drawbacks related to large equipment sizes, such as losses in production flexibility and mining selectivity. The combination of these results indicates interesting possibilities for the application of AHS on smaller equipment sizes.

The results obtained in the case study support the hypothesis that fleet selection can be integrated into an earlier stage of the mine design process. However, the precise improvement of the economic scenario due to various haul road characteristics and fleet selections could not be concluded. Instead, general statements are provided. Most of these limitations are the result of the poor availability of representational data regarding block models, and thus the ability to represent a realistic open pit mining operation. Nevertheless, it is clear that haul road characteristics and fleet selection can have a significant impact on a project's theoretical NPV.

ACKNOWLEDGEMENTS

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1   INTRODUCTION

Adequate open pit mine design and scheduling are getting increasingly important because of the decrease in higher grade ore reserves. For example, the average grade of copper ore mined in 2020 will be half of what it was in 1990 (Ausimmbulletin 2015). Besides this, deposits are becoming harder to extract due to, among others, an increase in the complexity of the geometry of the ore body and the increasing depth of open pit mines (Fytas, Hadjigeorgiou & Collins 1993). These developments result in generally higher expenditures and lower revenues, creating an even thinner line between profit and losses. This asks for more accurate mine designs and schedules, on both the short- and long-term scale in order to optimize the NPV of a project.

The mine design and planning process is a very large and complex problem, including thousands of variables that have to be taken into account, and can be seen as a circular process where decisions made at certain steps will affect the parameters used to determine those very decisions (see Figure 1). One relatively small, but very important element of the mine design process is the design of haul roads and switchbacks. These are the roads in the mine that are used to transport excavated material to the pit rim, the outer boundary of an open pit mine.

Both the dimensions and grade of haul roads have a significant impact on fleet selection and truck performance. Therefore, the underperformance of a haul road will have an immediate impact on mine productivity and costs. The geometry of a haul road will not only restrict the dimensions of the haul trucks that will be used in the operation, but it will also impact the pit contours and thus the amount of recoverable material. On its turn, the amount of recoverable material, which includes the ore, will impact the revenue of the project.
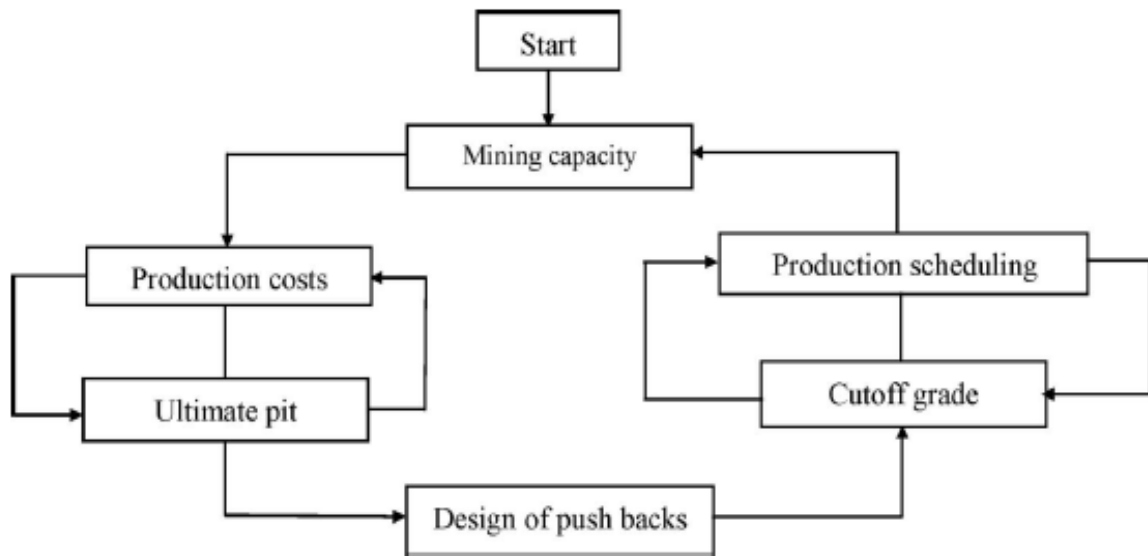
FIGURE 1. MINE DESIGN AND PLANNING CYCLE. DAGDELEN, 2001.

The (basic) geometrical design of a haul road is governed, but not bound, by certain input parameters such as the smallest mineable unit (SMU) or block size of the model. The determination of these parameters happens at a very early stage of the mine design process, where no detailed information about the eventual design is yet available. However, the decisions made in this part of the design process have a large influence on the configuration of the haul road dimensions.

Traditionally, the practice of fleet selection is done at the end of the mine design process, where, considering required production targets and designed haul road characteristics a (uniform) truck fleet is selected. Because of the predefined haul road dimensions not every class of truck will fit the design, limiting the choice in truck classes. This may result in a non-optimal fleet selection, which will have consequences for the project's NPV.

This study, executed in collaboration with equipment manufacturer Caterpillar, aims to investigate the possibility to implement fleet selection in an earlier stage of the mine design process. If the fleet selection is a criterion which is already taken into account in the early stages of mine design, possibly an optimal fleet can be selected for the specific design. This could result in a probable increase of (stable) output, a decrease in operational and capital expenditures, and thus an economically improved operation.

1.1   THESIS OUTLINE

This chapter will discuss the overall outline of the thesis. First, the context of the subject and the objective will be explained, after which the scope will be defined, depicting what will be included in the thesis and what will be left out of scope. In that section, the research questions that will support the objective are listed and explained. Finally, the last section will elaborate on the methodology that will be followed in order to find an answer to both the research questions and the objective.

1.1.1   CONTEXT

Nowadays, the fleet selection step takes place at the very end of the design process, where critical parameters that govern this selection, such as bench width and block size have already been made. This leaves ample room for alternative fleet sizes. The main reason this happens is that there is a disconnection between equipment manufacturers and mining companies. Where historically, equipment manufacturers are not incorporated in the early stages of the mine design process. If the equipment selection procedure is integrated into the design process, more optimal fleet matches can be achieved by reviewing different haul fleet size scenarios before the start of operations.

To come to an optimal matching fleet that meets the required production, calculations are performed using input data such as haul road length, gradient, width, truck capacity, cycle times etc. For this step, Caterpillar has developed a software tool, Fleet Production and Cost Analysis (FPC). FPC assists the user to predict fleet productivity, the time required doing a given job or jobs, and the cost for doing that job under a variety of conditions (Caterpillar no date). To be able to give better advice to customers regarding fleet selection, Caterpillar aims to play a role in the (early) design process of the mine by integrating FPC in the process.

1.1.2   OBJECTIVE

The main objective of this study is to identify at which stage of the mine design process FPC can be integrated, in order to optimize the equipment selection during the mine design process for Greenfield (a project in its earliest stage) projects. In the design, the potential for different haul road widths, gradients and switchbacks will be considered. Also, the advantages and disadvantages concerning these criteria related to an autonomous versus a manned fleet will be investigated. The thesis will be an investigation in the interaction between equipment selection (using FPC) and mine design.

1.1.3 HYPOTHESIS

It is possible to integrate fleet selection in an earlier stage of the mine design process, allowing for the analysis of various potential haul road scenarios and being able to make a decision on a more optimal fleet selection.

1.2   SCOPE

The most paramount component of the scope is to obtain an understanding of the possible position of detailed equipment selection (trough FPC) within the mine planning process. This will involve the investigation of different stages of mine design development and the tools that are used for each of these stages. Regarding the FPC software, it is important to identify which parameters are required to achieve an optimum solution regarding the fleet selection. With this information, an identification can be made showing at which stage(s) of the mine design FPC can be integrated.

Once these parameters have been identified, the goal will be to implement the fleet selection (through FPC) step in an earlier stage of the mine design process. To investigate the consequences of changes in the haul road design on the mine design and the project value, a sensitivity analysis will be performed on a case study. This analysis will, on one side look at different fleet options and determine the most optimal fleet selection through comparison in FPC. On the other side, the selected fleets will be related to different required haul road widths, and the impact of these variations in width on the stripping ratio will be calculated. Changes in the haul road width also have an impact on the required construction and maintenance costs, therefore general statements regarding these aspects will be given as well. The combination of these results allows for a sound determination of the most optimal solution and can clearly identify the differences between the various options.

With the alternative haul road scenarios, there is also the opportunity to investigate the possible advantages of using autonomy versus manned haulage equipment, including the relation both systems have with the haul road design itself. To make a sound comparison, it is vital to look at the requirements regarding haul road dimensions for both fleet systems and compare the advantages and disadvantages.

As a summary, the aim of this thesis is to answer the following research questions:

- What stages of mine design development are there and what tools are used for each stage?
- At which stage of the design process can FPC be integrated?
- What parameters does FPC require to make an optimum fleet selection?
- What are consequences of changes in haul road width, gradient and switchbacks on the mine design in an economic perspective?

- What are consequences of changes in haul road geometries related to an autonomous versus a manned fleet?

Besides the importance of describing what is included in the scope of this study, stating what is regarded as out of scope is also crucial. The following subjects are regarded as out of scope for this thesis:

- All the general advantages and disadvantages when comparing an autonomous and manned fleet;
- A study on other constraints during extraction and transportation (loading for example);
- Detailed study on the impact of haul road conditions (due to maintenance) on truck performance;
- Detailed economic analysis regarding the different fleet selections;
- The detailed differences of various mine design software packages

1.3   METHODOLOGY

To be able to answer the research questions, this study will be divided into two main parts. The first part will be a literature review. This will focus on mine design and mine planning, with special attention to the haul road design process and the parameters that impact the design and planning procedures. After that, the fields of equipment selection and autonomy will be reviewed. Finally, the key features of Caterpillar's FPC tool will be highlighted and clarification on the required parameters in order for the tool will be discussed.

The aim of the literature review is to give the reader an insight into the traditional way of mine design, and especially the haul road design process. Another goal is, with this knowledge, to identify at which steps in the mine design process it might be possible to implement fleet selection and with which software tools the design is usually carried out. Gaining a deep understanding of the FPC tool is of great importance since the goal is that the software will be used for the equipment selection part.

The second part of the thesis will be a case study, investigating the effects of the changes in haul route dimensions on the stripping ratio of different deposit sizes, compared to a base case scenario. For this part of the study mine design and planning software from Datamine will be used. With this software, different deposit sizes will be created out of a standard block model, and these models will be used to design the various haul road layouts. FPC will be used to determine realistic fleets for each of these deposit size scenarios, allowing to define the required haul road widths based on the truck models chosen.

With the obtained results, it is possible to compare the various haul road layouts and their associated fleet selections. The goal is to determine an optimal scenario based on this comparison. In order to determine this optimal scenario, the results of the case study will be analyzed and discussed, after which conclusions can be drawn and recommendations can be made.

2   LITERATURE REVIEW

The literature review is used to identify what the current approach and thoughts of the industry are, showing how the processes and problems are currently handled and where possible gaps or flaws occur. With this knowledge, a case study can be constructed that possibly improves or solves some of these issues. The literature review will comprise out of six main sections:

- Mine design
- Mine planning
- Equipment selection
- External factors
- Autonomy
- Fleet Production and Cost Analysis

One of the goals of these sections is to give the reader an insight into how the mine design and planning processes work in general. Besides this, the interaction between equipment selection and the haul road design process will be described, since this will be investigated in the case study. External factors that influence this process and the possibilities regarding autonomy will be discussed as well. Their importance regarding the case study will be handled in the discussion chapter.

Another purpose of the literature review is to obtain indications on how to find answers to the research questions, and use the attained results to narrow down the scope of the case study. Investigating which steps are currently taken by the industry to come to a final mine design, and the software tools that are used for this process are the most important aspects to achieve this. Since mine design and planning are very large topics on their own, with numerous specific facets, not all the aspects will be elaborated in full detail. Merely the subjects that are considered valuable for this study will be discussed. After these six sections have been delineated, conclusions can be drawn with a direct link of their relevance towards the case study.

2.1 MINE DESIGN

The terms mine design and mine planning are widely used, but also often interchanged. To clarify in which way both terms are used in this study, the following definitions are adopted. With mine design "physical layout and dimensions of a mine including macro issues such as the size and shape of pushbacks through to the layout and gradient of ramps" is meant (Tolwinski et al. 2007). In general, the design process involves the initial determination of the ultimate pit with all its dimensions, including pushbacks and the main characteristics of the haul roads. Mine planning embraces "the generic process of both designing and scheduling" (Tolwinski et al. 2007). This means a higher level of detail regarding the design, resulting in parameters that can be used for short-, mid-, and long-term schedules.

The steps that embrace mine design and planning will be explained in the sub-sections below. These steps will illustrate how the processes work in general and help to identify at which stage equipment selection could be implemented. Besides this, it will provide a framework for the case study that will be executed later in this thesis.

2.1.1 GEOLOGICAL BLOCK MODEL

The primary step of the mine design process is obtaining a geological block model (see Figure 2) which can be used as a basis for the mine design. In a block model, the deposit is divided into a three-dimensional grid and represented by equally sized blocks, which contain geologic information such as the ore grade, tonnage and rock characteristics (i.e. the rock type and geological zones). This information is obtained from drill-hole data, which is collected with drill-hole measurements and assigned to each block using available estimation techniques such as the inverse distance weighted interpolation technique, weighted moving averages, Kriging, etc. (Osanloo, Gholamnejad & Karimi 2008).
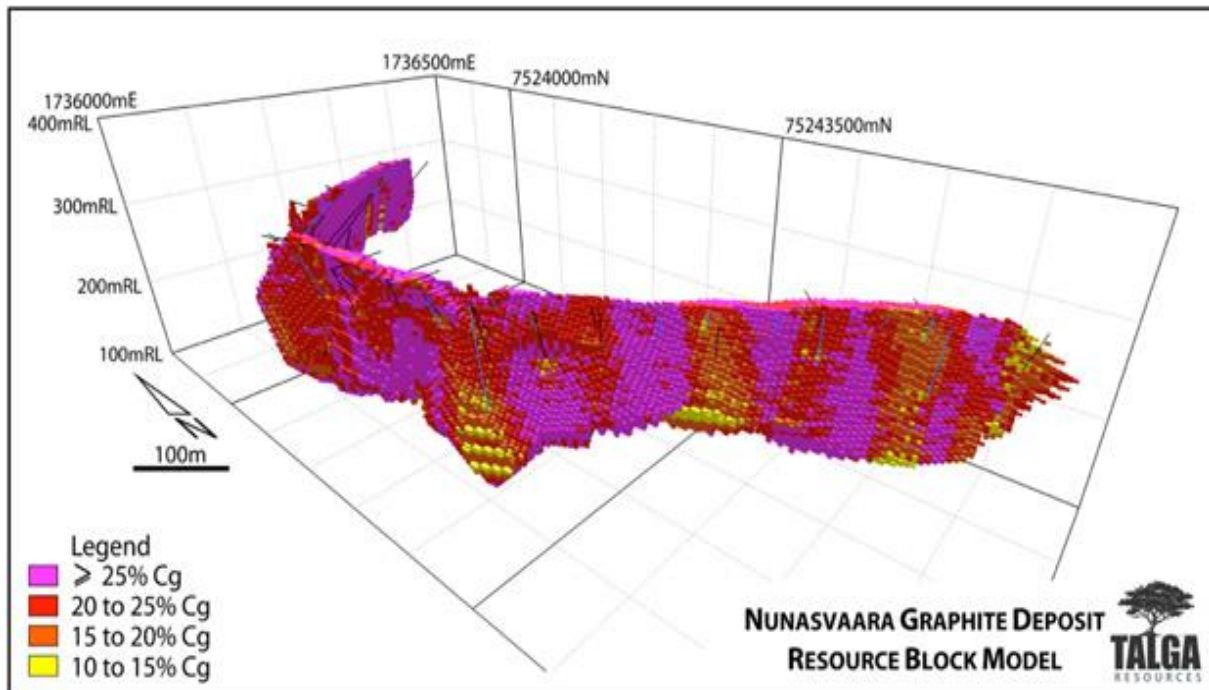
FIGURE 2. 3-D VIEW OF A GEOLOGICAL BLOCK MODEL. COLORS DEPICT A RANGE OF GRAPHITE (CG) GRADES. TALGA RESOURCES, 2018.

With this information, the block size of the eventual block model needs to be determined. In order to represent the deposit as accurately as possible, a high level of detailed information is desired. Theoretically, smaller blocks provide a more accurate estimation of its value compared to larger ones. However, smaller bocks also bring practical complications. For example, smaller blocks highly increase the number of equations that need to be solved due to the higher number of blocks in the model, and therefore will significantly increase the computational time (Philips 1991). Therefore, a general rule of thumb in open pit mining is that the minimum size of the block is not less than $\frac{1}{4}$ of the average drill-hole spacing (Hustrulid & Kuchta 2006)

The chosen block dimensions will condition mining dilution and selectivity, affecting the operation and mining costs (Jara et al. 2006). These aspects, dilution and selectivity, are not only governed by the block size, but also by the equipment that is used in the mining operation (Jara et al. 2006). Besides this, Baek and Choi (2017) state that the later determined bench height should be designed by considering the workable height of the excavation equipment, and that the bench width is empirically correlated to the bench height. This illustrates that the determination of the block size, early in the process, has an extensive impact on the future developments of mine design and planning.

2.1.2 ECONOMIC BLOCK MODEL

In order to generate an economical block model from a geological block model there are three main questions that require answering (Dagdelen 2001);

- Whether a given block in the model should be mined or not
- If it is to be mined when it should be mined
- Once the material is mined how it should be processed (i.e. whether it should be sent to a waste dump, processing plant or stockpile)

There are numerous different answers to these three questions, resulting in multiple different solutions. The reason behind this is that the economic parameters that define an economical block model, such as mining costs, processing costs, and the commodity price, are not constant. This can be explained by the fact that they are dependent on many (fluctuating) variables such as demand, fuel prices etc. Based on these parameters the economic value of each block can be determined, and based on that value the block can be categorized as waste or ore (Dagdelen 2001). However, it should be noted that this value excludes the cost of accessing the block. The economic future value of the block can then be obtained by discounting the original value to time zero, using a discount rate (Osanloo, Gholamnejad & Karimi 2008).

2.1.3 ULTIMATE PIT

Once the economic parameters are known, the analysis of the ultimate pit limit of the mine is undertaken to determine what portion of the deposit can economically be mined. The ultimate pit limit defines what is economically mineable from a given deposit with the current economic input (Dagdelen 2001). These calculations can be performed by commercial mine design software packages such as Datamine's NPVScheduler, which will be used later in the case study.

The generation of the ultimate pit can be done in various ways, and there have been extensive studies on this process, of which some notable papers are: Whittle (1990), Johnson and Barnes (1988) and Lerchs and Grossman (1965). The mine design software assesses each mining block's economic value, weighing the given costs required for extraction and revenue of that block. If this value is positive, it is considered as an ore block, suitable for extraction and processing, if not it is considered as waste. Besides this, the software has to take into account the costs of exposing the ore block, checking if the ore block's value can pay for the removal of overlying waste blocks (Dagdelen 2001).

The most used algorithm for this process is the Lerchs and Grossman (LG) algorithm, (Lerchs & Grossmann 1965). This analysis is based on the breakeven calculation that considers undiscounted costs of mining overlying waste and undiscounted revenue from the ore (De Kock 2007). Figure 3 illustrates the principle of the algorithm, known as a graph theory based algorithm, in four steps from top to bottom. The first step shows a schematic version of a deposit, surrounded by waste. The costs for removing a block of material (both ore and waste) is set at 4, where the profit of an ore block is set at 16-4 (revenue-costs). The second step shows the economic block model of this deposit, with waste blocks at a value of -4, solid ore blocks at a value of 12, and fractional ore blocks (partially ore and partially waste) at either 0 or 8.
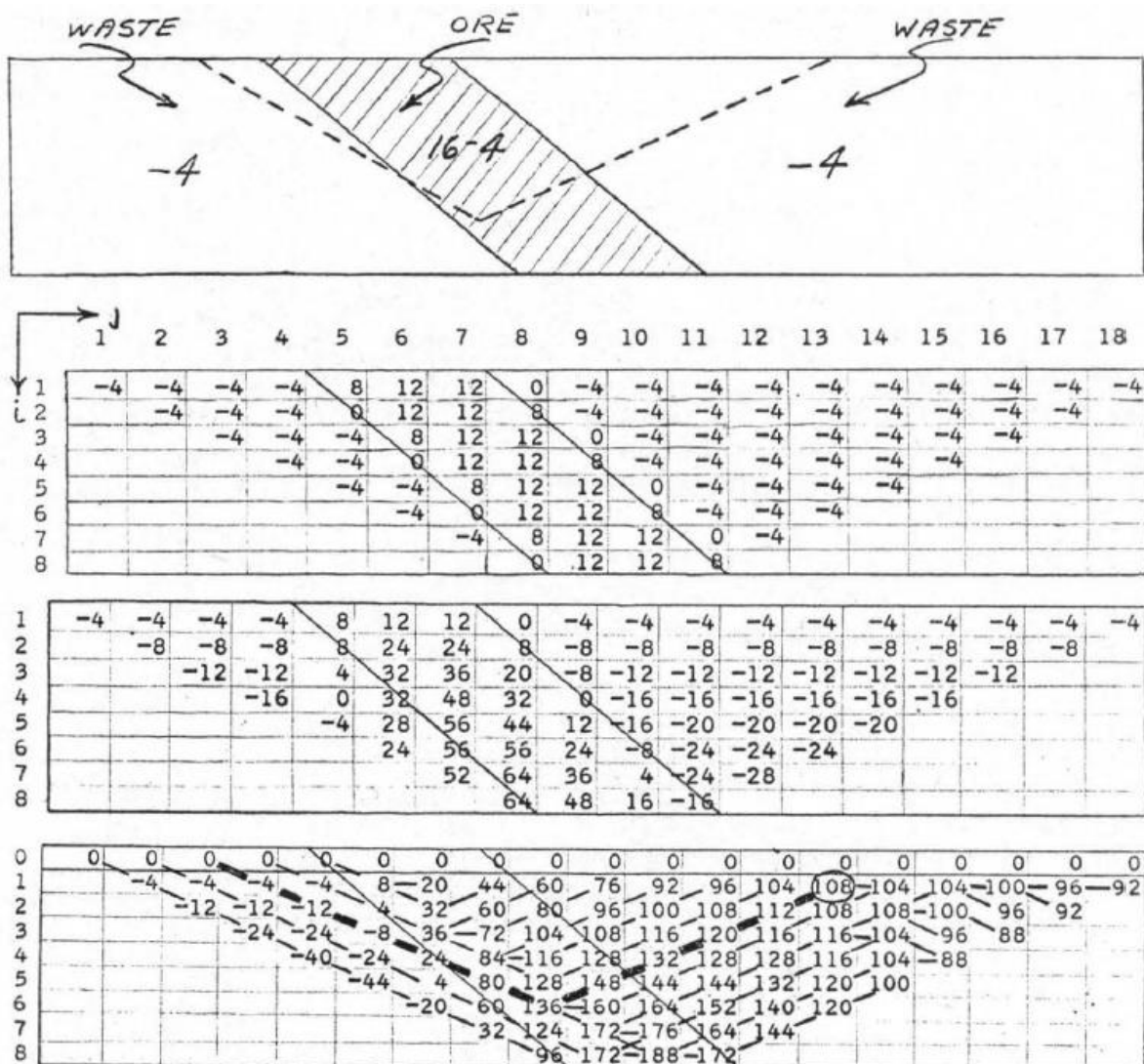
FIGURE 3. SCHEMATIC REPRESENTATION OF THE LG ALGORITHM. FROM TOP TO BOTTOM, (1) A SCHEMATIC REPRESENTATION OF A DEPOSIT WITH ORE AND WASTE VALUES, (2) THE ECONOMIC BLOCK MODEL OF THAT DEPOSIT, (3) THE COLUMN SUM VALUES, AND (4) THE CUMULATIVE BLOCK VALUES AND THE ULTIMATE PIT LIMIT. LERCHS & GROSSMAN, 1965.

The third step shows the cumulative value of extracting a column of blocks, where the algorithm sums up the values of a certain block and all blocks above it in the same column. The final step shows how the algorithm analyzes for each block if it can pay for its own extraction and processing, as well as the mining of overlying blocks necessary to reach that specific block. This is done by adding a row of zero's at the top (air blocks) and starting at the left limit of the block model working top-down. From left to right, the most positive value of the three blocks directly to the left of the specific block (i.e. diagonally above to the left, exact to the left and diagonally below to the left) is picked in order to calculate the cumulative sum of the cross-section. The block that is used for the calculation of the cumulative value is connected with a line to its resulting block. By selecting the most positive value in the upper row and working from right to left following those lines, the ultimate pit limit is presented. This is illustrated in the last step with a thick, black line. The value of the start point, which is circled and reads 108, is also the total value of the pit (Lerchs & Grossman 1965).

In order to determine the pit limit in 3-D, the optimum contours of the vertical 2-D sections are assembled. However, this does not always provide an optimum result, due to a mismatch with the slope constraints and the given pit angle. To overcome this, the walls and the bottom of the pit are "smoothed out", however, this possibly causes sub-optimal results and requires a great amount of computational effort (Lerchs & Grossman 1965).

It is important to note that the pit limit that maximizes the undiscounted profits for a given project, as shown above in Figure 3, will not necessarily maximize the Net Present Value (NPV) (De Kock 2007). This issue, in combination with the drawback of computational effort that was described previously, explains why nowadays other algorithms have been developed and are considered better alternatives by some (Dagdelen 2001). However, most of them still use the LG theory as a fundamental basis. One approach that incorporates the maximization of the NPV is, that from the ultimate pit limit obtained via the Lerchs and Grossman algorithm the Optimal Extraction Sequence (OES) is determined by the software. This OES depicts in which order the blocks within the ultimate pit have to be extracted to optimize the maximal theoretical NPV, and this approach is used in Datamine's NPVScheduler (Tolwinski et al. 2007).

2.1.4 Pushbacks

Within the ultimate pit, pushbacks are designed so that the deposit is divided into nested pits ranging from the smallest pit with the highest value per ton of ore to the largest pit with the lowest value per ton of ore (Osanloo, Gholamnejad & Karimi 2008). These pushbacks, or nested pits, are generated by

varying the economic parameters such as the commodity price, costs or cutoff grades gradually from a low value to a high value. By changing the commodity price, for example, from a low value to a high value, one can generate a number of pits in increasing size and decreasing average value per ton of ore contained in the pit (Dagdelen 2001).

To illustrate this, two mine sequences are shown in Figure 4 that represent different pushback scenarios. The first is simple to achieve, with a low complexity and excellent mining access. However, the stripping ratio in the early part of the life of mine is very high and decreases over time. This means that ore is accessed at a later stage (and thus revenue), and high costs are required for waste removal early in the life of mine. Therefore this sequence will lead to a poor NPV and is referred to as a worst-case sequence (regarding NPV). The second sequence shows that the ore is accessed earlier and the stripping ratio starts out low and ends up high. This sequence is more complicated than the first, but it will yield a higher NPV (Whittle 2011) and is referred to as the best-case scenario (regarding NPV). Usually, neither the best, nor the worst-case scenario is a realistic approach in pushback mining, so the actual outcome will be somewhere in between. Therefore, pushbacks are typically designed to be increasing in size but decreasing in average value per ton (Dagdelen 2001).
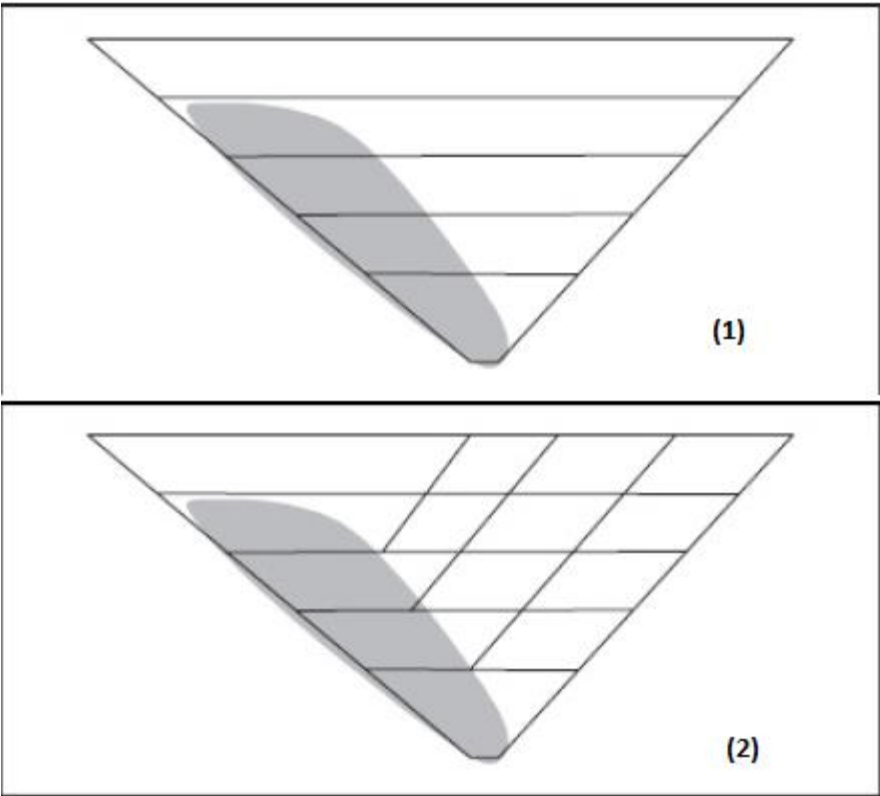
FIGURE 4. REPRESENTATION OF DIFFERENT PUSHBACK SEQUENCES, (1) REPRESENTING THE WORST-CASE SCENARIO, AND (2) THE BEST-CASE SCENARIO. WHITTLE, 2011.

The creation of pushbacks is based on the optimal order of removal of the blocks, and the basic objective is to create a series of pushbacks which meet some primary targets. Such as the ore tonnage to be won from each pushback, while respecting criteria such as the slope angle and the bench width of the pit (Tolwinski et al. 2007). This way, the pushbacks created at this stage will act as a guide during the scheduling of yearly production from different benches (Dagdelen 2001).

2.1.6 SCHEDULING AND CUTOFF GRADE STRATEGY

The goal of the scheduling process is to determine which parts of the pushbacks are mined in which period, with the aim of maximizing the NPV. To achieve this, the next step is to come up with (yearly) schedules by dividing the pushbacks further down into smaller increments. The biggest difference scheduling has with pushback generation, is that with scheduling a specific time is appointed to when a certain block should be mined, instead of only the sequence of mining (Dagdelen 2001). Due to the introduction of time, the blocks obtain discounted values, which is required to achieve the goal of maximizing the NPV. To be able to achieve an optimal NPV, multiple pushbacks can be mined simultaneously to balance both ore and waste production.

However, before determining the extraction schedule, the cutoff grade strategy should be defined to discriminate between ore and waste during the scheduling process (Osanloo, Gholamnejad & Karimi 2008). Most open pit mines are designed and scheduled by using cutoff grades that are calculated by using breakeven economic analysis (i.e. the grade at which revenue obtained is equal to the cost of producing that revenue) (Dagdelen 2001). However, the use of a breakeven cutoff grade during open pit planning results in schedules that maximize the undiscounted profits and is therefore not desired (Poniewierski & Hall 2016).

The cutoff grade that maximizes the NPV of the cash flows, and is preferred over the breakeven approach, is not only a function of economic parameters. Also, mining, milling, and refinery capacity limitations, as well as the grade distribution within the deposit play a role in determining this cutoff grade (Dagdelen 2001). The cutoff grade strategy that results in a higher NPV for a given project starts with a high cutoff grade during the initial years of the operation. As the operation proceeds, the cutoff grade gradually declines until it reaches the breakeven cutoff grade (Dagdelen 2001). This method ensures that high-grade ore is mined as soon as possible, and thus maximizing the NPV (Poniewierski & Hall 2016).

2.2 MINE PLANNING

With the ultimate pit limit, nested pits and pushbacks in place, the mine planning can commence. Mine planning is usually divided into three categories: long-term, short term and operational. A long-term plan defines the ultimate economic limit, or optimum pit limit (i.e. defines the size and shape of an open pit at the end of its life) (Johnson 1969). In other words, the long-term plan corresponds with the ultimate pit limit that was created during the mine design process previously.

Short-term plans are a sequence of depletion schedules leading from the initial conditions of the deposit to the ultimate pit limit, for which the pushbacks are used as guidance (Fytas, Hadjigeorgiou & Collins 1993). Each plan usually varies in duration from 1 to 10 years and provides information necessary for forecasting future production and capital expenditures (Johnson 1969). The operational planning is on a monthly to a daily schedule and involves the production requirements and the location of operation for that time slot.

For each mining period (long or short term) one of the most important goals is to keep the shovel movements at a minimum (i.e. the movement of a shovel from one location to another within the pit). This ensures maximum production time for the shovel and therefore results in a maximization of the profits realized within the mining period (Fytas, Hadjigeorgiou & Collins 1993). This is accomplished by:

- Minimizing the number of benches advanced per period
- Maximizing the amount of contiguous material removed per bench per period
- Keeping the material that must be mined left on a bench at the end of a mining period minimal, so that the shovel will not have to return to the same position later

Even more than mine design, mine planning is a circular process. The short-term plans are established using all the present and available data, which will increase the preciseness and reliability of short-term plans. Each mining plan affects the other plans and therefore any changes in short-term plans will have consequences for the long-term plans. This means that mine plans must be studied as a whole system in order to identify the interactions of the plans (Rahmanpour & Osanloo 2013).

This means that throughout the life of mine, the initial design, that was theoretically optimal but due to a lack of data low in reliability, will change multiple times, presumably resulting in a different final design than anticipated. In other words, the role of uncertainty is more significant in long-term plans

and this will render the preciseness of those plans (Rahmanpour & Osanloo 2013). This role of uncertainty also has an influence on the haul road design process. Generally, the complete haul road design is executed at the start of mine planning, or when the ultimate pit limit is known and the pushbacks are being designed (Dagdelen 2001). This means that there is still a high level of uncertainty regarding the future mine plans, and thus the haul road layout itself.

The haul road design includes the most important haul road characteristics such as the width, gradient, super elevation, switchback locations and haul road access points. To assist in the design process, there are some built-in applications in the mine design software that can be used to automatically design a road layout when its design characteristics are entered (Thompson 2011) .

However, to obtain these characteristics the user is still dependent on the empirical and subjective judgment of mining engineers (Baek & Choi 2017). One can imagine that if the short-term schedules vary too much from the initial schedules, this will have an impact on the long-term plan and also the predefined haul roads. Therefore the haul road design is reviewed during each of the (short-term) planning stages to ensure optimal design (Hawlitschek 2018). The details of haul road design will be further discussed in the following sub-section.

2.2.1 HAUL ROAD DESIGN

As discussed earlier, some of the initial steps for the haul road design are already taken in a very early stage of the mine design process. At the end of the mine design process or at the beginning of mine planning, after the pushbacks are defined, the initial complete haul road design and layout is determined. This can be done with integrated applications in the mine design software but it requires the input of certain road characteristics. These characteristics are still subjectively defined by a mining engineer based on the pit characteristics and required targets (Thompson 2011) and will be further discussed in this sub-section.

2.2.1A BENCHES

After the ultimate pit limit is defined, and the pushbacks and schedules are generated, the benches are designed. The bench height is defined as the vertical distance between each horizontal level of the pit. Unless the geological conditions dictate otherwise, all benches should have the same height

(Harraz 2015). The height of a bench will have a large impact on the final design of the pit and is dependent on (Harraz 2015):

- The physical characteristics of the deposit
- The degree of selectivity required in separating the ore and waste
- The size and type of equipment necessary to meet production
- The climatic conditions

To ensure that the maximum extraction is reached, the stripping ratio (i.e. the ratio of waste to ore that is mined) has to be minimized. Therefore, the bench height should always be set to the maximum allowable level, respecting the points mentioned above. For example, the degree of selectivity can be an important factor in determining the bench height. The bench height can range from 15 meters in large copper mines with a large, uniform ore distribution, to as little as 1 meter for uranium mines with very selective zones of ore (Harraz 2015). It can, therefore, be concluded that the bench height of an open pit mine is very much site-specific and dependent on local factors. This is important to keep in mind, illustrating that local characteristics have a possibly limiting influence on what is possible regarding the design itself.

It is important to note that benches can be used for various purposes, which also dictate the desired width. In general there are two ways a bench will be used in an open pit mine (Atkinson 2011) (see Figure 5);

- As a (catch) berm or safety berm, the purpose of this berm is to catch and stop rocks that are falling down the pit slope to prevent damage to equipment and slopes
- As a ramp/stepout or working bench, on this bench the shovel is located and there must be space to accommodate the traffic and maneuvering of haul trucks. These benches will obviously need to be significantly wider than the catch berms
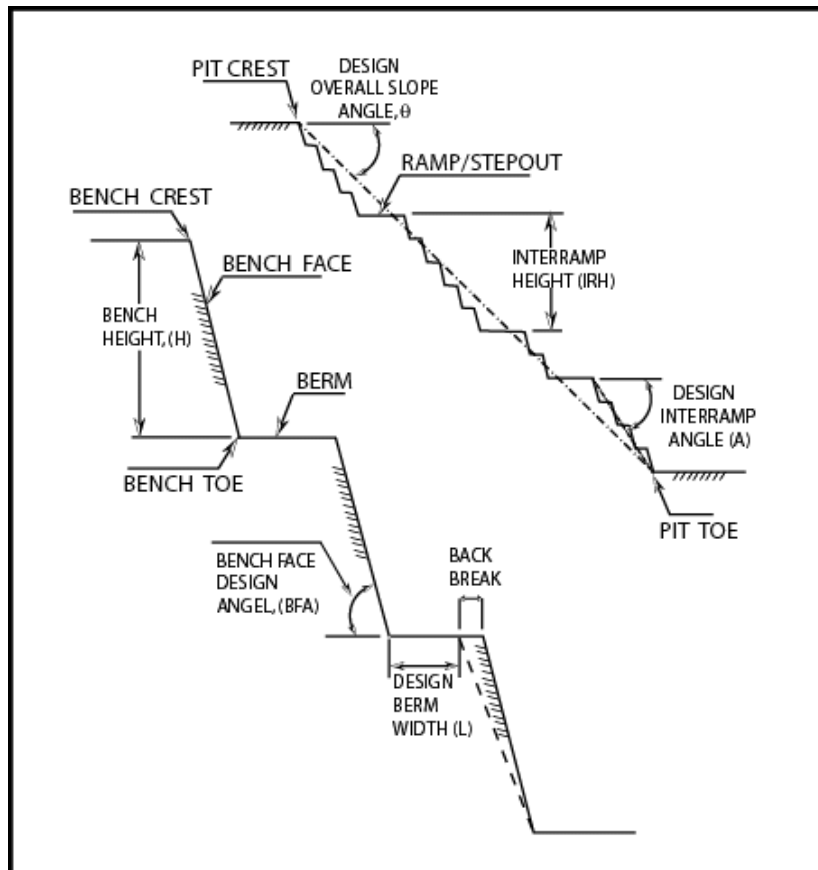
FIGURE 5. PIT SLOPE GEOMETRY PARAMETERS. MONDOL ET AL, 2013.

2.1.1B *HAUL ROAD WIDTH*

As described above, some benches will be designed to accommodate haul truck movement. The width required for these roads is dependent on the width of the largest haulage unit, legislation, and the intended use of the road. Usually, roads are designed with a dual lane configuration, so two trucks can pass each other as one goes down and one goes up, but this is also dependent on the scale of the operation (Tannant & Regensburg 2001).

According to Gowans et al. (2013), the general guidelines for the required width of a dual lane haul road is three times the largest haulage unit's width, leaving one-third of a truck's width on both sides and in the middle of the road for safe passing (see Figure 6). For the other required elements on a haul road, such as the safety berm and the drainage ditch another truck's width is added. This adds up to a total required bench width of around 3.5 to 4 times the width of the largest haulage unit, with some extra width employed in the curves (Tannant & Regensburg 2001). Note that these are just guidelines and the exact width of the haul roads may differ per project. This illustrates, just as was determined

with the bench height earlier, that local factors can play a very important role regarding the decisions that can be made during the mine design and planning processes.
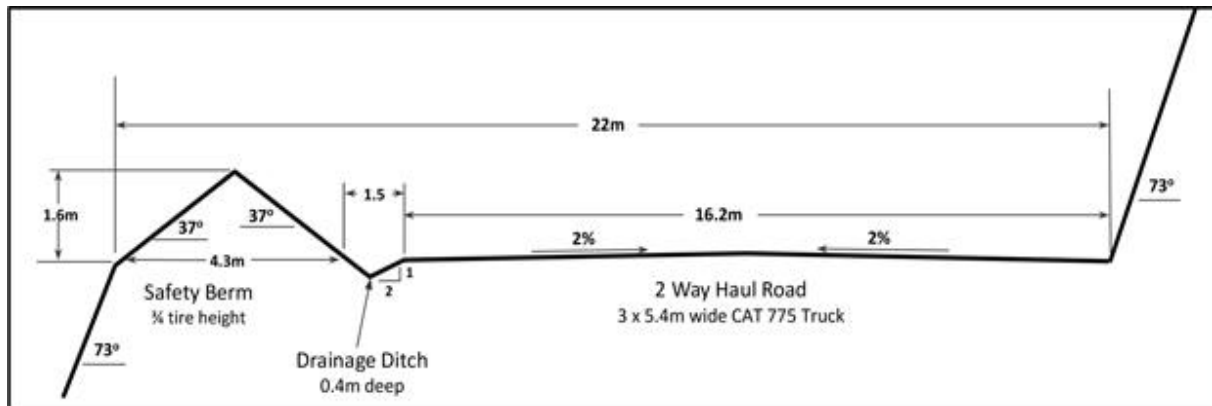
FIGURE 6. SCHEMATIC REPRESENTATION OF A DUAL LANE HAUL ROAD. GOWANS ET AL, 2013.

It may be noted that, relating these numbers to the investigation that will be carried out in the case study, a decrease in any of these width "factors" will result in smaller haul roads and less negative impact on the mine design. Some of these required widths are related to safety standards, such as the width in the middle of the road and the safety berm at the side. These standards were set in times that manned trucks were the only option. However, with the introduction of autonomy, these standards could possibly be lowered, or even left out, since there is no personnel at risk (Redwood 2018). These standards and other aspects related to autonomy will be discussed in more detail later in the literature review.

2.1.1C HAUL ROAD GRADIENT

In order for the haul road to climb between different benches and eventually reach the pit rim, a haul road is required to have a gradient (in degrees) or grade (in percentage). The grade is very important because it greatly influences the haul truck's performance and thus directly impacts the production (Caterpillar no date). If the grade becomes larger, the effective gravitational force on the truck increases, which increases its fuel consumption and accelerates the wear on the engine and the transmission (Caterpillar no date).

The chosen grade for a haul road impacts the distance the truck has to travel over the inclined surface. Increasing the grade will decrease the required inclined section of the haul road, and thus travel distance. This is, looking at fuel consumption, travel time, and engine and transmission wear a positive influence. However, it also illustrates the implications that arise, with one scenario having a shorter

but more severe impact on the truck's performance, and the other a longer but less severe impact. The possible variation concerning haul road grade might not be that significant, but when considering deep mines a few percent difference on the grade can have a large impact on the total inclined haul road length.

Imagine a very simplified version of an open pit with a depth of 600 meters and no horizontal haul roads (since these distances will be the same in both scenarios) (see Figure 7). The grade, α, in scenario (a) is 10% or 5.71 degrees, with a Δh of 600 meters this results in a slope length l of around 6040 meters trough simple calculations (see Equation 1).

$$\sin(\alpha) = \frac{\Delta h}{l} \qquad (1)$$

Scenario (b) has a grade of 8% or 4.57 degrees, just slightly less than scenario (a). Now, using the same equation, the resulting slope length l is around 7530 meters. This means for this scenario an increase in inclined haul road distance of 20%. This is just a simple example but it does give an insight in the increase in haul road length for varying gradients, especially concerning deeper mines.
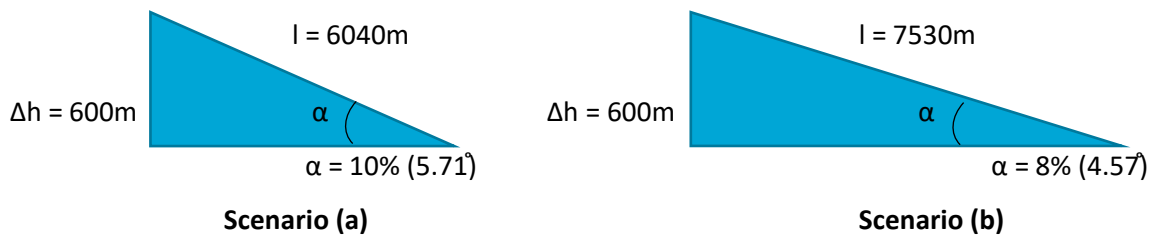
FIGURE 7. SCHEMATIC EXAMPLE OF INCLINED HAUL ROAD DISTANCE WITH VARYING GRADIENTS. NOT TO SCALE

Besides this, the impact of a higher grade haul road on the stripping ratio of the entire pit can be significant. Therefore designers will try and push the haul road grade to a (realistic) maximum, in order to minimize the stripping ratio, but maintaining an acceptable performance from the haul trucks. The ultimate determination of the grade depends on various factors such as the mine plans, economics, climate conditions, and optimal truck performance (Masabattula 2011).

Haul road grades can vary from -20% to +20%, but this only occurs on either very short sections or on temporary roads and is very uncommon. Usually (long term) haul road grades are below 10% and preferably at a maximum level of 8% (Tannant & Regensburg 2001). Studies show that this is the grade (8%) at which the lowest cycle times are realized, excluding construction time (Masabattula 2011).

However, Tannant and Regensburg (2001) and Masabattula (2011), only regard this 8% as the optimum grade when looking at the haulage truck's performance, where the loss of extractable material due to a higher stripping ratio is in this case not taken into account, which can be of significant impact. Therefore this is an aspect that will be investigated in the case study, where multiple designs with varying haul road grades will be created.

2.1.1D SWITCHBACKS

A switchback is usually a 180-degree curve which makes the haul road rise against the direction it came from (see Figure 8). Switchbacks can be very useful to ensure that a haul road remains on one side of the pit, for example, the preferred low side when concerning the topography or a geologically stable zone. According to Tannant and Regensburg (2011), this can ensure a safer operation, and can possibly influence the required travel distance positively in some cases.
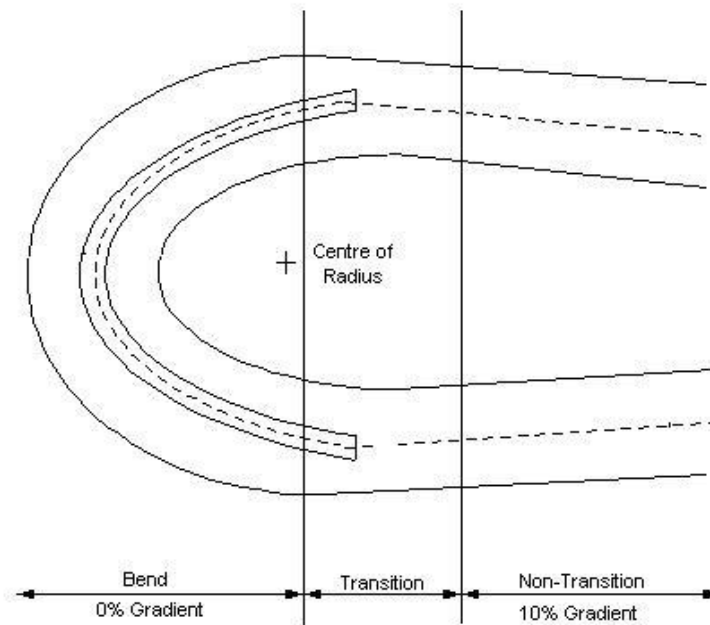
FIGURE 8. SCHEMATIC REPRESENTATION OF A SWITCHBACK WITH 3 ZONES. MININGINFOSITE, NO DATE.

However, there are also downsides related to switchbacks (Tannant & Regensburg 2001):

- The haul road on a switchback section needs to be extra wide to compensate for overhanging vehicles. This will result in an increase in stripping ratio and thus on costs

- Because of safety and vehicle wear considerations there are stricter speed limits on switchbacks, resulting in longer haulage cycles and a decrease in productivity
- Corners increase stress on vehicle chassis, tires and other parts, resulting in more frequent maintenance, which causes more downtime and higher costs

In general, there are two possibilities for creating a switchback; (1) an inclined or sloped switchback and (2) a flat or horizontal switchback. Figure 8 shows a flat switchback, with both ramp sections designed with a 10% grade, a transition zone to decrease the grade from 10% to 0% and the curve itself, at 0% grade. These flat switchbacks are preferred because they impose the least strain on the vehicle and are generally safer (Poniewierski 2018). However, Poniewierski (2018) only relates this preference towards the truck's performance and wear, and not the impact it has on the mine design.

The grade of an inclined switchback has to be lower (2% to 3% maximum) than the grade of the straight sections because of the increased rolling resistance imposed by the curve. This is such as minimal effective gain compared to the downsides and is therefore not considered worthwhile. Note that in some cases graded switchbacks might be necessary, however, if the choice is there, flat switchbacks are preferred (Poniewierski 2018).

To further decrease the strain and increase the maximum speed in the corner, super-elevation can be integrated into the design. This makes the corner banked at generally 3 to 4% (Kaufman & Ault 1977) and counteracts the centrifugal force on the vehicle (see Figure 9). Besides this, it also improves drainage and thus the road conditions. The curve radius of a switchback is dependent on the turning circle of the haulage trucks that will operate them and the corner speed that is requested.
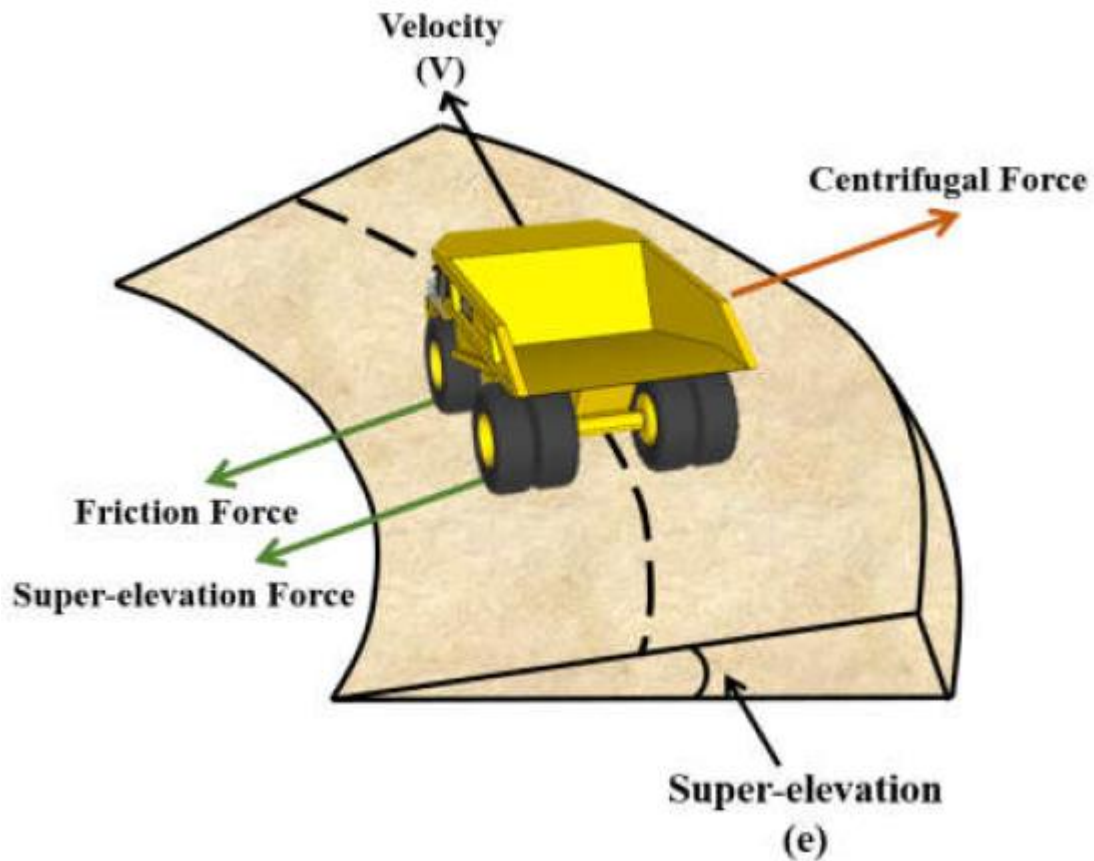
FIGURE 9. SCHEMATIC REPRESENTATION OF SUPER ELEVATION IN A CURVE. TANNANT AND REGENSBURG, 2001.

The conditions that justify the use of switchbacks in a mine are very site-specific and are dependent on a lot of variables such as the topography, depth of the deposit and (local) geological conditions. This makes it difficult to quantify the impact of increasing or decreasing the number of switchbacks on the final mine design.

The preference is to avoid switchbacks, since under equal circumstances they will always have a larger negative impact on the mine design compared to a normal spiraling haul road (Baek & Choi 2017). Therefore in the case study, the designs will be made without switchbacks. What will be done to investigate the impact of switchbacks instead, is a theoretical analysis on switchbacks based on the obtained results in the case study, illustrating what impact the implementation of switchbacks will have on these cases.

2.3   EQUIPMENT SELECTION

The open pit equipment selection problem has a significant impact on the open pit design and production planning (Bazzazi, Osanloo & Soltanmohammadi 2008). This is caused by the fact that the ultimate pit limit, which was determined prior to equipment selection, is based on economic conditions, pit geometry, and production rates. These factors have a major impact on equipment sizing and selection, which in turn can also affect the design parameters that were used for the ultimate pit, presenting itself as a circular problem (Berkhimer 2011).

In mine equipment selection, the type, size, and the number of units are major considerations, and these three items are strongly interdependent. For example, the use of large equipment will subsequently lead to a lower number of units required. Regardless of which approach regarding the selection process is used, the main goal of the process is to satisfy the production rate requirements while minimizing the mining costs (Bozorgebrahimi, Hall & Blackwell 2003).

In order to make appropriate equipment selection decisions, in addition to the deposit characteristics, the operating scenario must be considered (Bozorgebrahimi 2004). The deposit characteristics embrace parameters that are of a nature that cannot be changed, such as the ore grade and the amount of reserves. However, the operating scenario encompasses two main fields of parameters that can be controlled or determined (see Figure 10). These two fields are (Bozorgebrahimi 2004):

- Mine planning needs

These are all the factors a mine planning engineer can decide and change accordingly, for example the daily production rate and the mine layout.

- Operating environment

These are all the factors required, or have to be taken into account to be able to execute the desired mine planning factors, such as amount of personnel and shifts per day.

Deposit Characteristics

A- Deposit Characteristics:
1- Reserves
2- Geometry
3- Topography
4- Groundwater
5- Hardness and abrasivity
6- Grade distribution
7- Swell factor
8- Diggability
9- Ground bearing pressure
10- Rock mass quality, structure

Operating Scenarios

B- Mine Planning Needs:
1- Daily production rate
2- Bench geometry
3- Mine layout
4- Scheduling
5- Matching factors

C- Operating Environment:
1- Personnel
2- Weather
3- Shifts per day
4- Management
5- Maintenance
6- Training

Equipment Size

Equipment Size Sensitive Variables

A- Direct Impact:
1- Productivity
2- Capital cost (Basic price, Commission, Shipment, Insurance, etc)
3- Operating cost (Tires, Fuels, Maintenance,...)
4- Flexibility and versatility
5- Reliability
6- Infrastructure: Haul roads, etc
7- Minimum working area
8- Risk management (lost production)
9- Efficiency
10- Utilization
11- Waste dump management
12- Matching factor: drills, loaders, haulers

B- Indirect Impact:
1- Selectivity and dilution
2- Environmental management
3- Safety
4- Milling efficiency - cost
5- Mine longevity
6- Community

FIGURE 10. EQUIPMENT SIZE CONSIDERATIONS AND EQUIPMENT SIZE SENSITIVE VARIABLES. BOZORGEBRAHIMI, 2004.

Figure 10 shows the variables/ parameters that are considered in the process of equipment size selection at the top and the variables that can be influenced by equipment size at the bottom (Bozorgebrahimi 2004). As was stated by Bozorgebrahimi, Hall and Blackwell (2003), the basic goal of equipment selection is to satisfy production rate requirements while minimizing the mining. Therefore the first and most important consideration in the size selection process is the required daily production rate. Generally, this is determined by considering the reserve, the market, the company's production strategy and the expected payback period (Bozorgebrahimi 2004). Once this has been decided, in

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combination with the mine layout, the equipment sizes are determined. The selected equipment size then influences the mining costs, which eventually affect the optimized pit and its dimensions (Bozorgebrahimi, Hall & Blackwell 2003).

In today's mining industry there is a mentality of "bigger is better" regarding equipment sizes. Experience has shown that larger equipment has reduced total cost by improving productivity in big mines (Gilewicz 2002). However, there are also indications that this strategy may not always be advantageous. These indications concern difficulties that are caused by ever increasing equipment sizes such as complexity, dilution, lost production and lack of flexibility. With decreasing ore grades and a higher sensitivity related to fluctuating commodity prices, mines need to go deeper and thus steeper. This results in the fact that to reach these deeper ore bodies, the overall pit angle has to increase, making it more and more difficult to implement larger equipment and besides increasing the overall haul distances.

The dependence on fewer but larger pieces of equipment to exploit economies of scale for improved competitiveness tends to especially reduce a mining system's inherent flexibility (Dunbar, Dessureault, & Scoble 1999). Therefore Krause (2001), suggest that blindly increasing the equipment size to achieve more production at a lower cost might not be the best option, as can be seen in Figure 11, which is supported by Gajigo and Dhaou (2015). In this figure, A, B, and C stand for different scenarios that illustrate the uncertainty in the development of cost per ton versus the equipment size.
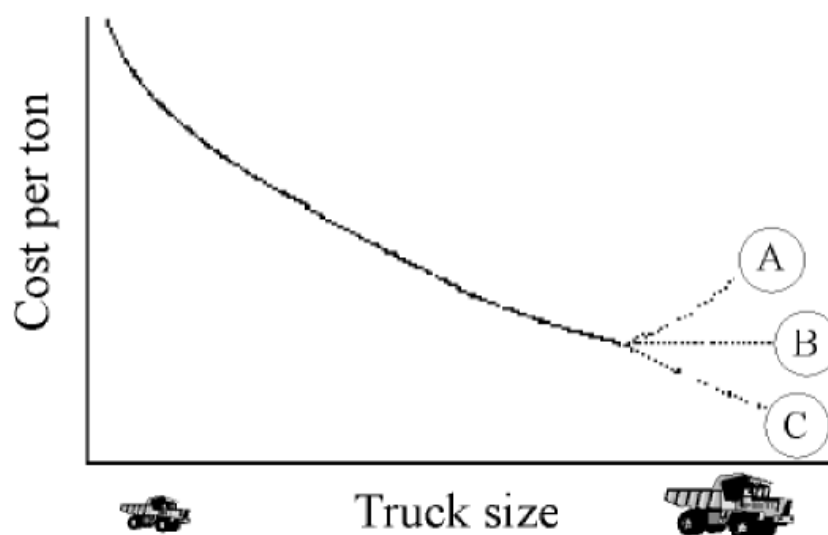
FIGURE 11. UNCERTAINTY IN COST PER TONNE OF PRODUCTION VERSUS THE EQUIPMENT SIZE. KRAUSE, 2001.

In mining, flexibility represents the ability to adapt to internal or external changes in operating conditions. External change, for example, might relate to market prices, environmental conditions, community development, industrial relations, regulations, and government policy. Internal change might relate to grade distribution, ground conditions, workforce, equipment and infrastructure (Dunbar, Dessureault & Scoble 1999). With increasing equipment sizes, the ability to adapt to these changes will decrease due to a lack of flexibility, resulting in possible economic losses.

The studies mentioned base a minimization of mining cost solely on capital and operational expenditures related to the truck and shovel, which is a somewhat simplistic approach. Besides what Bozorgebrahimi, Hall and Blackwell (2003) and Krause (2001) suggest, the selected equipment size also influences the infrastructure (in particular the haul roads) and the minimum working area. These two factors have a significant impact on the mine layout and its ultimate dimensions, and thus also on the entire value of the project (Berkhimer 2011). This shows that it is clear that equipment selection, as well as mine planning and mine design itself can be seen as an iterative process, which has to be repeated multiple times to come to the best site-specific solution, where local conditions can play an important role regarding the range of possibilities.

Where Bozorgebrahimi, Hall and Blackwell (2003) and Bozorgebrahimi (2004) state that the production rate is the most important factor regarding equipment size selection, this does not imply that there is one rigid outcome possible. Based on the production rate, the loading equipment is selected, and based on that the haulage units are selected. However, one can imagine that there are many possibilities in selecting a loading tool, or combination of loading tools, especially as production increases.

These decisions have a significant impact on which haulage units will be required, and these units on their turn impact the haul road width and thus the mine design, including its economic potential. Investigating which loading tool is the best suitable is therefore not as simple as looking at the production rate, mine layout, and other factors. For each deposit different scenarios regarding loading, and thus haulage equipment should be analyzed. This allows for the determination of effects on the mine design and mining costs, in order to come to a (site specific) optimal solution.

2.4 EXTERNAL FACTORS

The design and planning processes described in the previous sections are based on an average or ideal scenario, without any extra limitations regarding the design of an open pit mine. However, in reality, there are numerous external factors and risks that have to be taken into account when making a mine design (Park & Matunhire 2011). These factors and risks will quite possibly limit the possibilities of the eventual design. This is supported by Dimitrakopoulos, Martinez and Ramazan (2007), who state that a critical source of technical risk is geological, including the expected ore grade and tons within a given design layout.

Besides the external factors that are described in this section, other factors such as the production rate influence the number of possibilities regarding the mine design (see Figure 12). As described earlier, the production rate greatly influences the equipment selection. The selected equipment and its dimensions on their turn impact the mine design and thus limit the spectrum of possibilities. Another one of these limiting factors is the implementation of Autonomous Haulage Systems (AHS), which will be described in more detail in the next section. These limitations illustrate that for each scenario, site-specific parameters narrow down the options related to a mine design, and result in the fact that an optimum design is heavily based on local factors and cannot be generally adopted.

Available design options without restrictions

Loss of options due to external factors (geological, technical, economical, environmental)

Loss of options due to required production rate (equipment selection)

Remaining design options
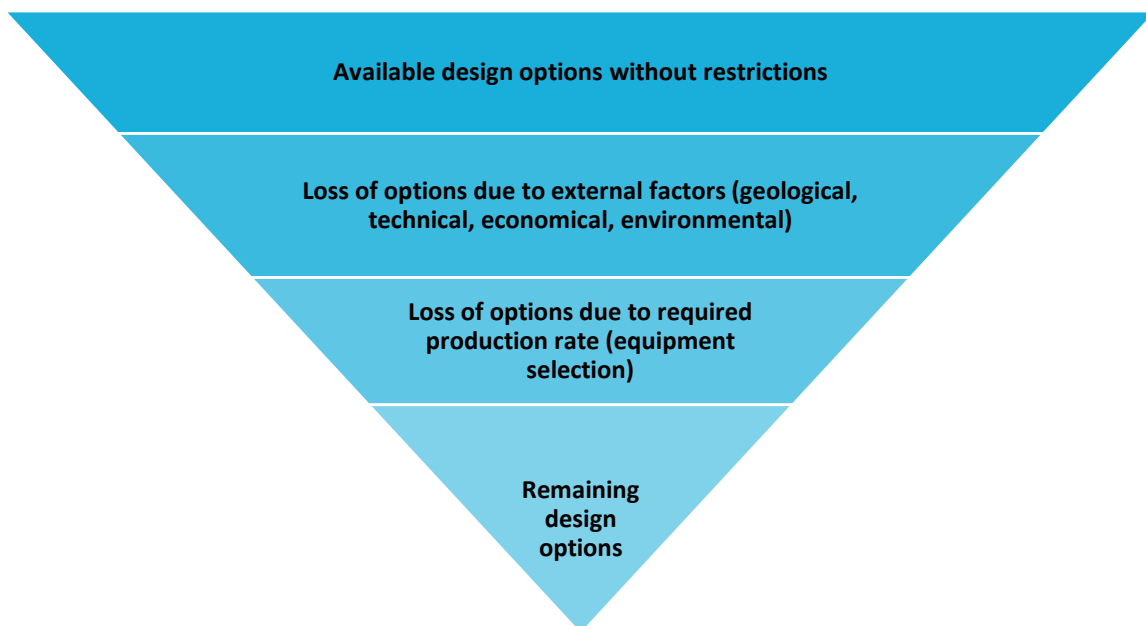
FIGURE 12. FACTORS THAT INFLUENCE THE AMOUNT OF DESIGN OPTIONS THAT REMAIN VIABLE

The external factors that affect the mine plans could be classified as controllable and not controllable factors (Rahmanpour & Osanloo 2013). For example the uncertainty of a commodity price is uncontrollable, however, ore grade certainty can be reduced by increasing the exploratory working in the mining area (Rahmanpour & Osanloo 2013). These factors have to be identified prior to the design process and can be very site specific. The factors can be grouped into four general categories, (1) Geological, (2) Technical, (3) Economical and (4) Environmental, Social, and Political (Eggert 2010), and (Rahmanpour & Osanloo 2013), which are summarized in Table 1.

TABLE 1. UNCERTAINTIES RELATED TO EXTERNAL FACTORS AFFECTING MINE DESIGN AND PLANS. RAHMANPOUR & OSANLOO, 2013. INCLUDING ADDITIONS

Categories	Site specific factors that can affect the mine design and plans	
Geological	1. Ore Type 2. Physical rock properties 3. Depth and shape of deposit 4. Grade distribution 5. Definition of resource and reserve 6. Geological interpretation 7. Delineation of ore and waste	8. The boundary between ore and waste 9. Geologic complexity 10. Block size 11. Topography 12. Hydrology 13. Presence of contaminating elements
Technical	1. Quality and quantity of exploratory workings 2. Slope modelling 3. Cutoff grade 4. Mineable reserve 5. Pit geometry and haulage system 6. Reliability and efficiency	7. Mining method and technology used 8. Loading system 9. Mining company's objective (e.g. NPV or mine life maximization) 10. Post mining land use 11. Infrastructures
Economical	1. Ore price 2. Capital cost 3. Operational cost 4. Pit slope 5. Mineable reserve 6. Stripping ratio 7. Cutoff grade strategy 8. Mine size	9. Mine life 10. Ore recovery 11. Dilution 12. Environmental costs 13. Reclamation costs 14. Social costs 15. Payback period 16. Investment possibilities
Environmental, Social and Political	1. Safety (standards) 2. Local legislation 3. Local climatic conditions 4. Location of deposit (country) 5. Working ethics / shifts 6. Remoteness of project	7. Availability of (skilled) workforce 8. Daylight hours 9. Workforce unions / strikes

2.4.1 EXPLANATION OF FACTORS

As mentioned earlier, the combination of these site-specific factors can have a significant impact on the final mine design. The factors that are listed in Table 1 can be subdivided into two classes, dependent and independent factors. For example, the ore type and grade uncertainty are independent factors since they do not rely on other factors to be determined. Factors such as block size and slope modeling are therefore classified as dependent factors (Rahmanpour & Osanloo 2013). From each of the general categories a few factors will be explained in more detail below, in order to illustrate the possible effects they have on the design.

- **Geological** – physical rock properties – independent factor

The different rock properties that occur within the deposit dictate the boundaries of what the possibilities are regarding, for example, maximum slope angle, maximum haulage road grade, and type of excavation. This will directly impact the possibilities within the mine design, and will also impact the extraction method and production rate, which on their own will also influence the mine design limitations.

- **Technical** – mining company's objective – independent / dependent factor

Each mining company might have a different primary objective due to the company's structure and values, where one might value NPV maximization above mine life maximization and vice versa. This decision is not only company specific, but it can also be dependent on the location of the intended project. For example, if a project is located in a politically and socially unstable region, the company might prefer to maximize the NPV with a minimum life of mine (LOM), in order to be exposed to as less risk as possible over the shortest amount of time. Therefore this factor is valued as both independent as dependent. Choosing which objective is preferable has a large impact on the design, and is thus very important to take into account.

- **Economical** – environmental, reclamation and social costs – dependent factors

If the proposed project area is bound by a protected environment or villages are located on site, these are crucial factors to take into account. Reclamation and resettlement costs can run into very high numbers, but can also be an uncertain factor. Investigating design possibilities where such costs are avoided is therefore usually worthwhile, but will subsequently change the original design plans.

- **Environmental, Social and Political** – local climatic conditions – independent factor

The local climatic conditions play a significant role when concerning a mine design. For example, the difference between winter and summer can be in some places tremendous. In Scandinavian countries the temperature can vary from -35 ℃ in winter to +35 ℃ in summer. This has a large impact on the geotechnical capabilities of the host rock, due to freezing and thawing of groundwater. If these changes are not taken into account when making the design, pit slope failure could be the catastrophic result. Another important aspect of climatic conditions is rainfall, especially around the equator where severe rainstorms can occur. Designs that are made in these areas will have to take into account the effect of erosion on ramps and pit slopes due to these rains, allowing for less steep designs than originally intended.

2.5   AUTONOMY

In relation to the previous sections, the use of Autonomous Haulage Systems (AHS) can have an impact on equipment selection and thus the mine design itself. Therefore it is necessary to investigate what the possibilities concerning the implementation of AHS are in relation to the economic scenario of a project. However, the implementation of AHS is also related to certain preconditions. These preconditions need to be addressed in order to determine if, and when the implementation of AHS would be possible, let alone be beneficial. These aspects will be further discussed in this section.

Equipment fleet performance is the main determinant of operating cost and production rate in a mine. The operating cost of an equipment fleet is expected to add up to 20-35 percent of the total operating cost in a mine (Gölbaşi & Dagdelen 2017). Equipment operating cost is a time-dependent cost function of fuel and tire consumption, costs of spare parts, lubricants, maintenance crew wages, auxiliary tools, etc. (Gölbaşi & Dagdelen 2017). If these two pillar stones, production rate and operating cost, could be increased and decreased respectively, significant cost savings could be achieved. Autonomous Haulage Systems (AHS) have demonstrated a success in lowering operating cost and increasing the production rate and is expected to improve further in the future (Redwood 2018).

Besides the fact that AHS have proven to increase production and decrease operating costs for certain operations, according to Meech and Parreira (2011), they will also improve the safety of a mining operation. Due to the repetitive, monotonous work of truck operators, driver fatigue causes up to 65% of all haulage truck accidents (Modular Mining 2011). With the integration of AHS, this percentage can possibly be brought down to zero, since the operator factor can be eliminated. These impacts already show the potential of AHS, however, other parameters related to AHS need to be discussed as well.

Where automation of large machines is already well advanced, the technology of AHS is limited by two factors; the extent to which automated trucks interact with other equipment and if the system integrity can be incorporated at a reasonable cost. All previous successful autonomous applications have the following characteristics (Nebot 2007):

- Structured environment;
- Well defined automated task requirements;
- There is a need for the solution;
- Site willing to adopt the new technology;
- Simple / robust technology;
- No interaction with manned machines

Where some of these points are clearly met, the environment where surface mine haul trucks need to operate show contrary characteristics:

- Rugged environments (Dust, moisture, extreme weather conditions)
- Dynamic and often unpredictable
- Unstructured and often defined by geology
- Difficult to sense and costly to incorporate integrity
- Difficult to build simple, effective and robust models
- Significant interaction with manned machines

Since the publishing of Nebot (2007), technology has advanced and some of these points are no longer considered (major) problems. On the other hand, there are still some issues that need to be overcome, especially the interaction between manned (maintenance) equipment and autonomous trucks for example. These issues require further investigation and illustrate the implications still related to AHS today.

Implementation of AHS is also dependent on the size of the operation, where only very large deposits (and thus large dump trucks) are considered suitable for the implementation of autonomy at this stage (Lever 2011). The main reason behind this is the high costs of investment related to the implementation of AHS, and the suitability of the deposit type (Lever 2011). This shows that the implementation of AHS cannot be generally adopted and is dependent on site-specific factors, such as for example the deposit size and grade distribution. Relating this to the previous section on external factors, the implementation of AHS will narrow down the available options regarding the mine design even further (see Figure 13).
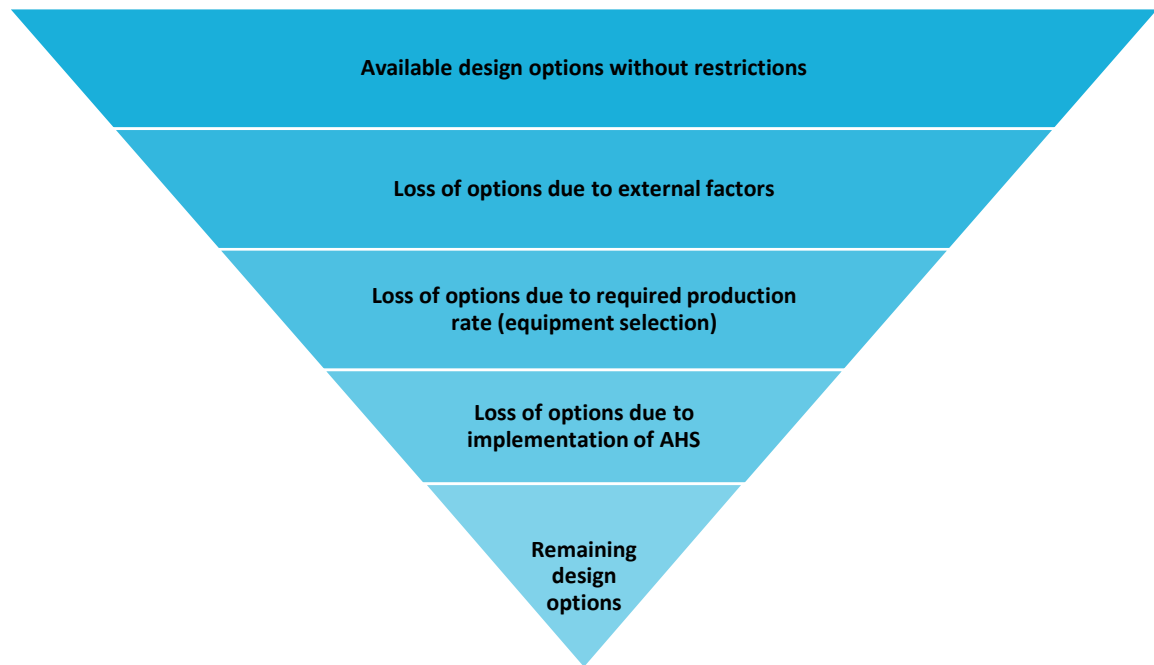
FIGURE 13. FACTORS THAT INFLUENCE THE AMOUNT OF DESIGN OPTIONS THAT REMAIN VIABLE, ADDITION TO FIGURE 12

Besides these implications and the before mentioned advantages related to a decrease in costs and an increase in production and safety, there are other potential benefits related to AHS. The implementation of AHS results in a driving accuracy of several centimeters, and the positions and speed of the trucks are controlled within very fine tolerances. Due to this increase in precision compared to a manned truck and the exclusion of human drivers, studies such as Redwood (2018) suggest that there is less allowance required. This is substantiated by the idea that the necessary strict safety standards, between truck and ramp edges or other trucks traveling in the opposite direction, could be removed. This would theoretically allow the ramp width to be reduced.

Reducing the ramp width will have several economic benefits, since the overall pit slope can become steeper. It will generally result in a reduction of waste stripping, meaning less costs, and ore zones at the bottom of the pit could possibly become economically viable to extract, resulting in an increase in revenues (Bozorgebrahimi 2004). Since the main goal of the case study is to investigate the impact of alternative haul road widths on the mine design, the conclusions obtained could be used to make statements related to the benefits of implementation of AHS in mining operations, which will be addressed in the discussion.

2.6 FLEET PRODUCTION AND COST ANALYSIS (FPC)

The main goal of this part of the literature review is to give an insight into how FPC works and identifying which parameters are required inputs. This section does not have the purpose to act as a manual on how to operate FPC, for this Caterpillars' FPC Guide or manual can be reviewed (see FPC Guide no date). Therefore it will not go into full detail regarding the software but mainly touches upon the most important features and briefly explains their purpose and parameters.

"The Fleet Production and Cost Analysis program is a software package that assists the user in predicting fleet productivity, the time required doing a given job or jobs, and the cost for doing that work under a variety of conditions" (FPC Guide no date). The program works with fleets that move material from one location to another over one or more courses. A fleet consists of haulers, loaders and support equipment and a course defines the hauling conditions over which a specified quantity of material is transported from its original to a new desired location. The variables used to define a course are distance, rolling resistance, grade, and speed or passing restrictions (FPC Guide no date).

Fleet Production and Cost Analysis is useful for comparison and estimating purposes. A cost or production comparison can be made between fleets moving material over a single course (haul profile) or over a group of courses. Usually, in a comparison, the fleet that can move the materials for the lowest cost within a prescribed time period would be the most desirable (FPC Guide no date).

A very important feature of FPC is the information the software has on different machine's rimpull curves. The software uses this information to calculate the retarding and acceleration of the vehicle when approaching for example switchbacks or driving on inclined surfaces. This results in a very accurate approximation of the truck's speed, which helps to determine more realistic cycle times.

2.6.1 INPUTS

The FPC program requires certain input data to be able to make above mentioned comparisons or estimations. There are three interfaces that can be used for the input of data;

- Project input
- Fleet input and
- Course input

Some of these inputs variables have to be determined by the user itself, some can be taken from the Caterpillar database. By making different hauling and loading combinations, with different parameters, the user is able to determine the most optimal fleet for the required job. This starts with creating a study within the software and defining the project input.

In this part general information regarding the project can be written down and also the desired input type, U.S. or metric can be defined. Also default inputs such as, operating hours per period and operator efficiency have to be determined here. Once this part is completed the user can start creating the desired fleet(s).

At the fleet input stage the user has to add haulers and loaders in which ever quantity is desired. To make things easy, Caterpillar has incorporated its own product lines within the database, so all of Caterpillar's machines can be chosen, with sometimes all the detailed variables such as engine performance, capacity etc. already in place. If required, it is also possible to adjust these standard values for specific conditions for example. Also some competitors' equipment is incorporated in this database, and there is also an option to configure equipment to the operator's requirements as well.

The next stage is where the course characteristics are put in. At the course input sheet, the user can either import a predefined course from excel or GPS data, or fill in the data separately. A course is usually broken up into segments with the same characteristics for a specified length (see Figure 14).

	Distance (meters)	Rolling Resistance %	Grade Pct.	kph Limit	Description	Stop	Gear Limit	Stop Time (Minutes)
1	50.00	3.00	0.00	40.00	load area	☐		
2	100.00	2.00	3.00	40.00		☐		
3	60.00	2.00	3.00	15.00	switchback 1	☐		
4	50.00	2.00	2.00	40.00		☐		
5	60.00	2.00	2.00	15.00	switchback 2	☐		
6	55.00	2.00	7.00	40.00		☐		
7	60.00	2.00	7.00	15.00	switchback 3	☐		
8	210.00	2.00	9.00	40.00	main ramp	☐		
9	60.00	2.00	9.00	15.00	switchback 4	☐		
10	37.00	2.00	0.00	40.00		☐		
11	50.00	3.00	0.00	40.00	dump area	☐		

(● Haul ○ Return 792 meters)

FIGURE 14. EXAMPLE OF A COURSE BROKEN UP INTO DIFFERENT SEGMENTS IN FPC

In Figure 14 it can be seen that each of the segments require a specified distance, rolling resistance, grade percentage and if applicable, a speed limit. This way it is very easy to implement specific parts of haul roads where different conditions apply compared to the rest, for example on switchbacks. Note that the switchback sections shown in this course are an example on how FPC can be used, and do not represent the course used for the case study.

The total distance is calculated by the program and if required, the return route can be mirrored from the haul route (if the return route is the exact same route as the haul route this is a very useful feature). Also, other very important aspects of the project have to be defined during the course input. These are the loose density, bank density and the quantity of the material that is to be transported.

Results from a project are obtained at the production and cost interface. Here, all the detailed information is stated which can be used for the comparison or estimation of production, costs and required time by different fleets. It includes cycle times, detailed haul and return times per segment, required fleet size for the job, fleet match, costs etc. Looking at these results the user can make decisions on the desired fleet or make slight adjustments to find an even better solution.

3   CASE STUDY

This chapter consist out of the following sections:

- Introduction
- Methodology
- Parameters
- Results

3.1   INTRODUCTION

It is the goal of the case study is to obtain results regarding the economics of a project related to various haul road characteristics and layouts. One side of these results will be obtained through FPC, creating multiple fleets with varying truck sizes per scenario. These fleet selections will be related to the haul road widths they require, of which the impact on the mine design based on a changing stripping ratio will be calculated. This will be done using Datamine's StudioOP and NPVScheduler software programs. Once both the results from the FPC software and Datamine have been obtained they can be related to each other and conclusions can be drawn.

From the FPC analysis, general statements will be made regarding costs related to various equipment sizes. This will include capital investment (CAPEX), operating costs (OPEX) and cost per ton. It is expected that the values regarding the costs per ton for the various fleet selections will not differ a significant amount for the cases that will be investigated. This can be explained by the fact that the deposit sizes that will be investigated are not quantified as very large. However, when considering larger deposits, these differences are expected to be more profound.

3.2 METHODOLOGY

The literature review has illustrated that designing multiple scenarios with different block sizes is probably not very realistic and also not useful. Besides the fact that it will take a lot of effort, as mentioned earlier, the block size is not the single most important factor regarding the final haul road characteristics. Therefore the creation of multiple models with varying block sizes is not regarded as an added value to the project.

What will be done instead is creating multiple scenarios with different bench widths. This allows for the creation of different haul road scenarios with varying road widths and grades to allow for multiple truck sizes. After this step, using FPC, precise haul road widths can be determined based on the fleet selections, which will honor equal production rates. Next, the goal is to calculate the increase or decrease in tonnages for the different designs, since wider roads require a higher stripping ratio. Combining these two results it might be possible to make statements regarding which truck size and haul road layout offer the best perspective regarding the economic scenario of a project. This approach will, therefore, be further investigated and explained in the case study.

The basis of the case study relies on the (economic) block model that can be used for the different pit geometries, since this is the framework that is used to define the ultimate pit limit. In order to ensure realistic results, the block model needs to reflect the characteristics of a real deposit as accurately as possible. The block model is used to determine the ultimate pit limit of the different deposit sizes, and based on those results the mine designs can be made. This process will be executed with equal economic parameters for the different pit sizes to ensure the only altering variable is the haul road configuration. A detailed explanation of the construction of the block model, mine designs, and the parameters used will be given in the following sections.

The goal is to create three different pits, representing a relatively small, medium and a large open-pit gold operation. The choice for multiple deposit sizes is made since it is expected that the obtained results will also be dependent on the size of the deposit. The reason that gold is chosen as a commodity is mainly that there is extensive data regarding gold deposit sizes and grades available. Besides this, the block model that was obtained already represents a gold deposit. Further details regarding the argumentation on these choices can be found in the respective section on parameters.

Obtaining actual data from operating mines that can be used to create these three different pits has proven to be very difficult, since this is sensitive information that mining companies do not like to share. Also Caterpillar itself was not able to provide data that could be used for this purpose. Therefore the decision was made to create a block model based on tutorial data. Thanks to the generosity of Datamine, a tutorial dataset was made available representing a gold deposit suitable for open pit extraction, which was used for the case study.

Once the mine designs of the three scenarios have been made, three different fleet selections per scenario will be made in FPC, ranging from a small to a medium and large equipment size, respective to the size of the operation. Here the medium size fleet will act as a reference, depicting a "base case" scenario (see Table 2). The fleets have to meet the same production, and therefore there will be a larger quantity of small trucks required compared to the larger truck size option. From these truck sizes, the required widths of the haul roads can be determined. With this known, the haul road design can be integrated into the mine design, and from there the results on the economics of the project can be assessed (see Figure 15).
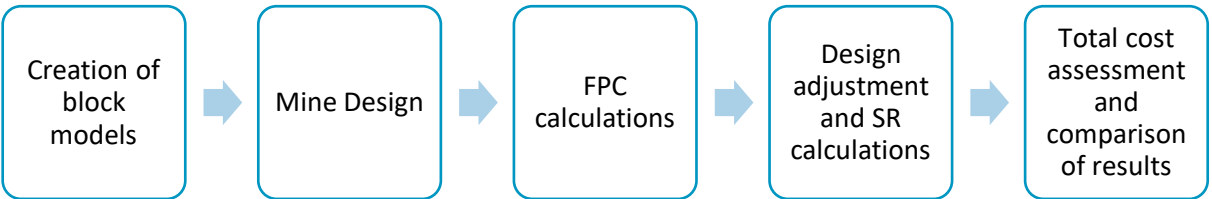
FIGURE 15. STEPS THAT WILL BE TAKEN IN THE CASE STUDY

Besides this, the "base case" scenario of the large pit will be designed with a varying haul road grade (see Table 2). The grade of a road does not limit the choice of equipment (as long as the grade remains in workable limits), since each truck model can operate under these limits. Therefore it is not necessary to investigate a change in haul road grade on the different equipment sizes. The change in grade will have an impact on the truck's performance however, and this effect will be described theoretically. Table 2 shows the different scenarios that will be investigated with NPVScheduler, StudioOP and FPC during this case study.

Parameters	Small Pit (0.77Mt 7.5gr/t Au)	Medium Pit (5.7Mt 2.9 gr/t Au)	Large Pit (13Mt 1.6 gr/t Au)
Small fleet size, haul road grade 8%	X	X	X
Medium fleet size, haul road grade 8%	X	X	X
Large fleet size, haul road grade 8%	X	X	X
Medium fleet size, haul road grade 6%			X
Medium fleet size, haul road grade 8%			X
Medium fleet size, haul road grade 10%			X

Some of the other scenarios will be discussed theoretically based on the obtained results. This decision is made because the obtained results can be extrapolated to other scenarios since, in essence, they correspond with the investigated scenarios. This will be explained in the respective chapter. These scenarios include:

- Same pit sizes with a uniform ore grade for all pits
- Amount of switchbacks present within the pit
- Alternative ore grade
- Alternative haul road grade
- Alternative haul road width

3.3 PARAMETERS

The commodity that is used for the case study is gold. This decision was made because there is an extensive amount of benchmark data available regarding open pit gold mines, which is accurately described by Singer (2012). This information can be used as a reference to create a block model with a realistic size and grade. Three of these deposit types that Singer (2012) has investigated were used for the case study since they have the highest frequency of supporting data.

The chosen deposit types are Comstock epithermal vein deposits, sediment-hosted gold deposits, and hot spring gold deposits, which will represent a relatively small, medium and large operation respectively (see Figure 16). From these three deposits, the average ore tonnage and grade were taken to be used in the block models (see Table 3). These deposit types are mainly present in the USA, and can all be valued as relatively small deposits compared to other well-known deposits, such as Witwatersrand.
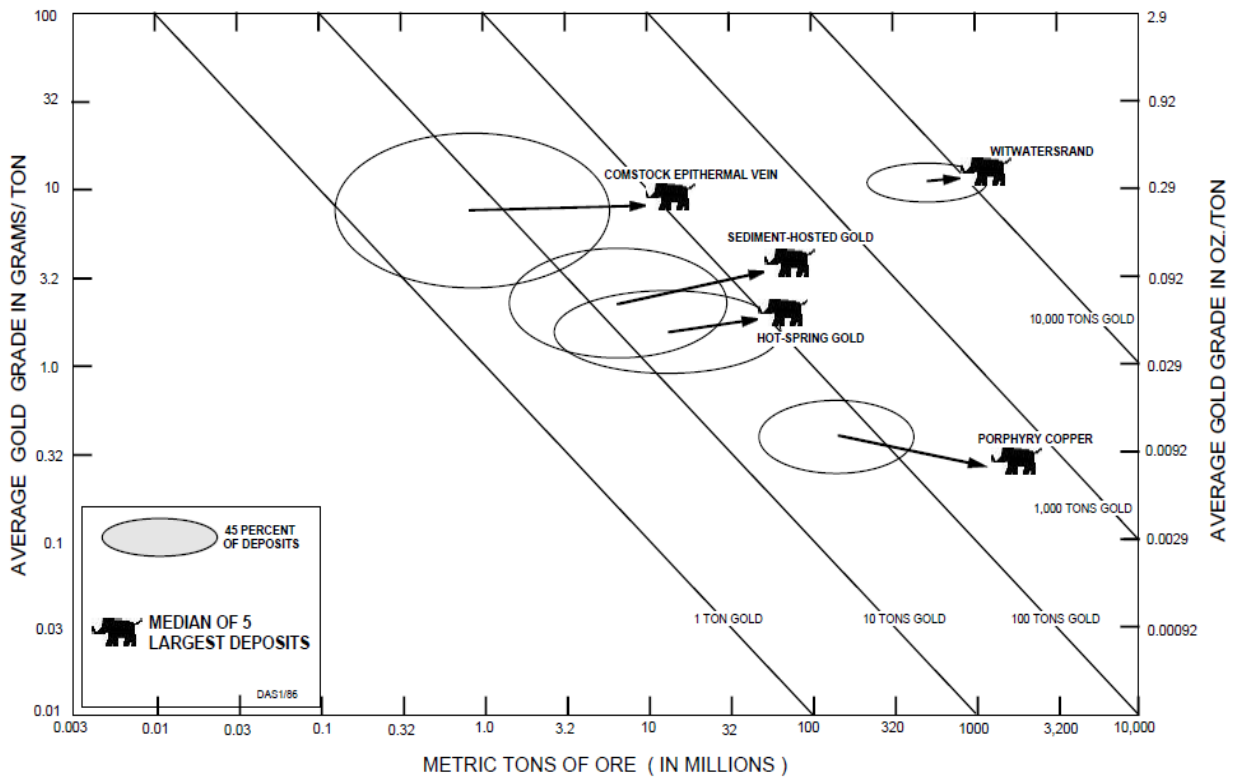
FIGURE 16. GOLD GRADES AND TONNAGES BY DEPOSIT TYPE. MEDIAN GRADE AND TONNAGE LOCATED AT THE CENTRE OF EACH ELLIPSOID. SINGER, 2012.

TABLE 3. DEPOSIT TYPES AND THEIR AVERAGE RESERVE AND GRADE

Deposit Type	Average Reserve (Mt)	Average Grade (gr Au/t)
Comstock Epithermal	0.77	7.5
Sediment-Hosted	5.7	2.9
Hot Spring	13	1.6

The main reason for using these specific deposit types is that they are well studied and statistics have been made based on dozens, to over a hundred deposits, which results in reliable average data. The average grade and tonnage values were taken from different studies on these deposit types, which are all summarized in Singer (2012) (see Figure 16). The Comstock epithermal vein deposit type is described in Cox and Singer (1986), which studied 41 deposits related to this deposit type (see Figures 17 and 18). The sediment-hosted deposit type is described in Berger et al. (2014) and studied 118 examples, of which the grade and tonnage plots can be seen in the Appendix-A. The hot spring deposit type is studied in Berger and Singer (1987) and was carried out on 17 examples, the associated plots can be found in the Appendix-A.
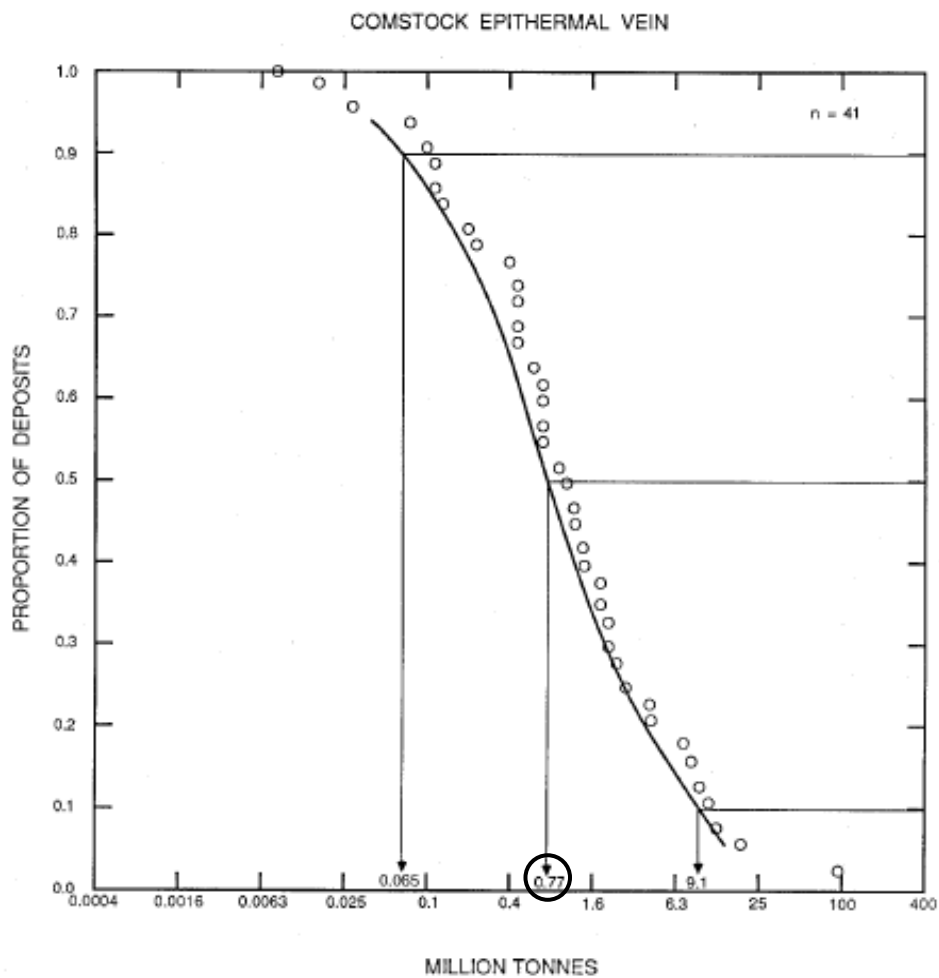
FIGURE 17. CUMULATIVE FREQUENCY PLOT OF ORE TONNAGES FOR COMSTOCK EPITHERMAL VEIN DEPOSITS, OF WHICH THE AVERAGE TONNAGE (CIRCLED) WAS USED FOR THE CASE STUDY. COX AND SINGER, 1986.
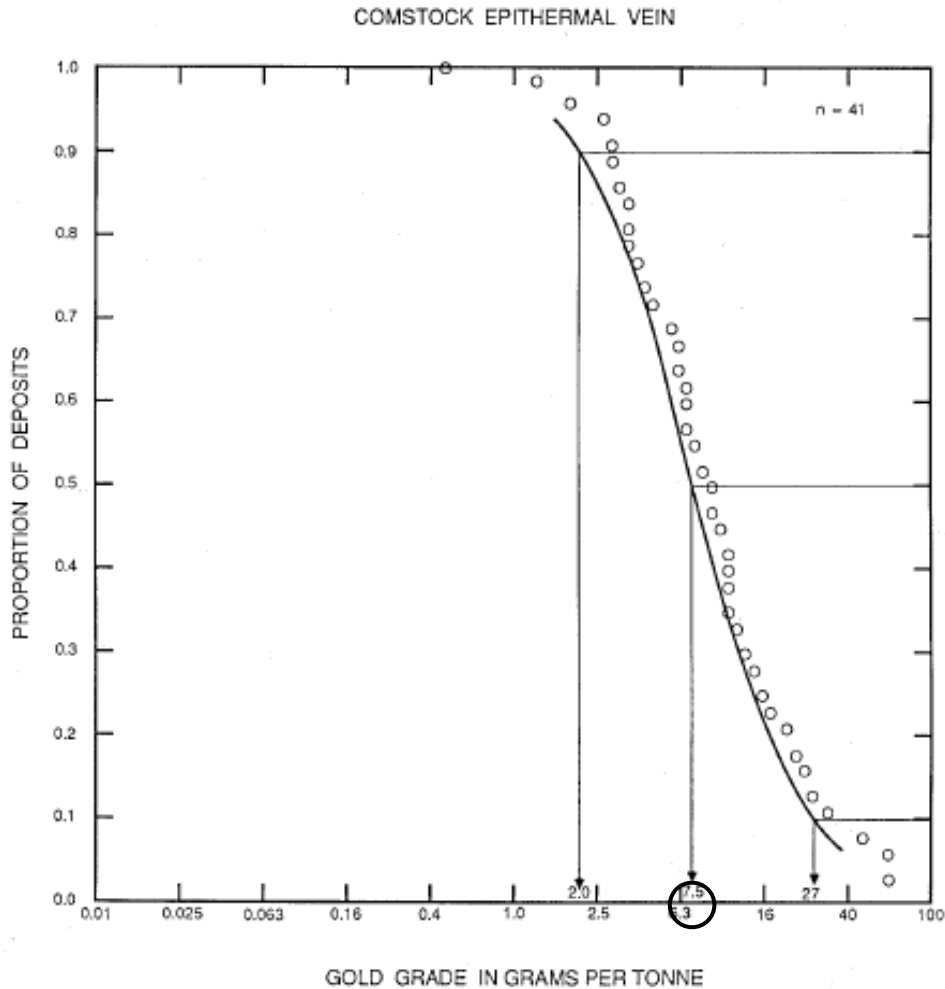
FIGURE 18. CUMULATIVE FREQUENCY PLOT OF GOLD GRADES FOR COMSTOCK EPITHERMAL VEIN DEPOSITS OF WHICH THE AVERAGE GRADE (CIRCLED) WAS USED FOR THE CASE STUDY. COX AND SINGER, 1986.

Another reason for the use of these specific deposit types and especially their size, which is considering mining standards very small, is the lack of workable data. With this data, the block models, or the drill-hole information required for the construction of a block model is meant. Since Caterpillar was not able to provide this information due to confidentiality reasons of its customers, the work in the case study was dependent on external sources to provide the data. Thanks to the generosity of the company Datamine, of which the software is used for the determination of the ultimate pit and the mine designs, a standard block model could be obtained. This block model is not considered as very large, but it suits the described deposit types and due to a lack of alternatives it is used as a basis throughout the case study. The effect of the use of such small deposits on the intended results will be discussed in more detail in the results and discussion chapters.

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Now the desired deposit tonnages for the block models are known, it is possible to estimate the daily production. For these estimations, Taylor (1977) developed an empirical formula based on numerous cases (see Equation 2). Taylor's formula has been modified and altered multiple times, mainly to accommodate a larger and more modern dataset, and therefore the later edition will be used in the case study.

$$Production \ (mt \ per \ day) = 0,0143 * Tonnage^{0,75} \qquad (2)$$

$$Taylor's \ Formula \ (1977)$$

Besides this, the formula has been altered to describe the relationship to specific commodities more closely, of which one is specific for open pit gold and silver mines. This specific alteration on the original formula was done by Singer, Menzie and Long (1998), which is based on 41 open pit gold and silver mines (see Equation 3).

$$Production(mt \ per \ day) = 0.416 * Tonnage^{0.5874} \qquad (3)$$

$$Singer, Menzie, and \ Long's \ Formula \ (1998)$$

Singer, Menzie and Long (1998) found out that the appropriate production rate for open pit gold and silver projects was significantly higher than what Taylor's formula suggests (see Equations 2 and 3). These equations and some other modified versions are also described in Figure 19, where the used deposit sizes and production rates of the case study are stated with an "X". It is important to note that these formulas are empirical and just approximations, however, they do give an initial idea regarding the scale of the required production.
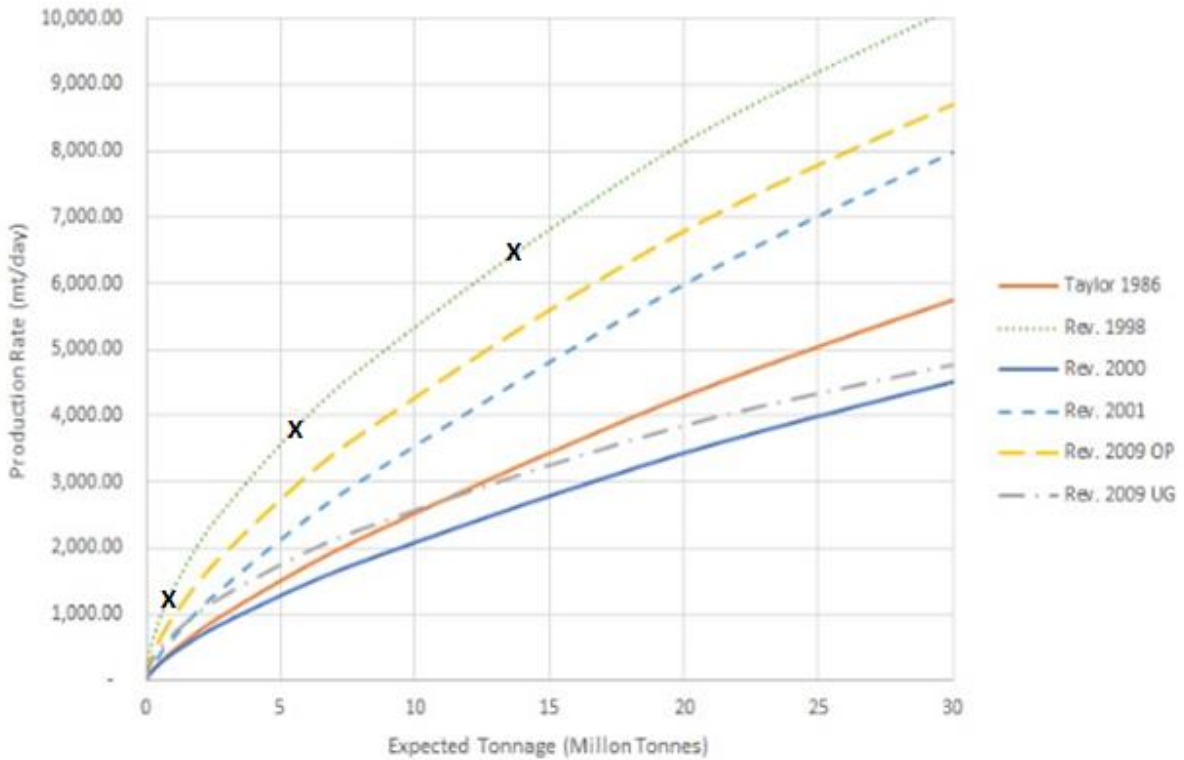
FIGURE 19. TAYLOR'S FORMULA FOR THE CALCULATION OF THE PRODUCTION RATE FROM THE EXPECTED TONNAGE. ALSO THE MODIFIED VERSIONS ARE INCLUDED. X MARKS THE USED DEPOSIT SIZES. SINGER, MENZIE, AND LONG, 1998.

For this specific study the formula of Singer, Menzie and Long is used since it describes open pit gold and silver deposits, which corresponds with the case study. Also it is more up to date than Taylor's original formula. Using the formula, the following production rates are achieved (see Table 4). Since these values are approximations, rounded values will be used in the remainder of the case study for ease.

TABLE 4. CALCULATED AND ROUNDED PRODUCTION FOR EACH OF THE DEPOSIT TYPES.*A YEAR IS BASED ON 365 DAYS

Deposit type	Reserves (Mt)	Calculated production (metric tons/day)	Rounded production (metric tons/day)	Production (metric tons/year*)
Comstock epithermal vein	0.77	1193	1200	438 000
Sediment hosted	5.7	3868	3900	1 423 500
Hot spring	13	6278	6300	2 299 500

It can be concluded that the estimated production rates represent relatively small operations, especially regarding the Comstock epithermal vein deposit. To determine the usefulness of this deposit in particular, first, a mine design and fleet selection will be attempted. These results and conclusions can be reviewed in the respective section.

3.4 RESULTS

The parameters that will be used for calculations in both of the software packages will be explained in this section, and the obtained results will be listed. In the first part of this section the results obtained in NPVScheduler will be elaborated and in the second part those of StudioOP.

3.4.1 INTRODUCTION

To be able to calculate the desired economic value of the different pits, two computer programs will be used. The initial creation of the block models, the economic model, schedules etc. will be performed using Datamine's NPVScheduler. The results obtained can then be exported to Datamine's StudioOP, a software package used to design open pit mines. Here the haul roads will be added in the design and the final calculations regarding changes in stripping ratio can be made. Once these results are obtained, the analysis and discussion can take place.

With the parameters that were obtained in the methodology, it is now possible to create three drill-hole databases, each representing one of the deposit types. The only aspects that differ for the three cases are the size and the average grade of the deposits, which correspond with the values depicted in Table 4. The topography and depth from the surface to mineralization of the deposits will be kept constant throughout the three cases. Besides, as explained in the literature review, there are many other parameters or external factors that might have an influence on the mine design. These external factors have been deliberately left out of scope. This way it is ensured that the adjusted mine designs will only be altered because of the changes in haul road profiles, instead of by other variables.

3.4.2 NPVSCHEDULER

The results listed in this sub-section are those of the medium-sized deposit. The other two deposits have different sizes and grades, and therefore for these calculations, alternative parameters will be used. These parameters and results are not implemented in this section itself since else this will result in an exuberance of tables and figures, which will not improve the readability. Therefore only the results of the medium-sized deposit will be used to illustrate and clarify the context, and the results obtained for the two other cases can be reviewed in the Appendix-B.

The first step when starting a new project in NPVScheduler is obtaining a drill-hole database and a topography. Such a database can be obtained in several ways, for example from a mining company itself. For the case study, a drill-hole database and topography developed for tutorial purposes are used as a basis, which is slightly modified to suit the objective better.

3.4.2A TOPOGRAPHY

The topography that is used for this project is the same for the three different deposits. This ensures that the topography does not have an impact on the results when comparing the different pit sizes. The topography was obtained via the website of the USGS, which enables users to "clip" the topography of a certain area if the data is available. A location in the USA was chosen with not much elevational differences, since a highly undulating topography will have a more significant impact on the mine design, which is not desired. For this study the topography is merely a "supporting" characteristic, which preferably has as less impact on the design itself as possible. A topography has to be implemented in order to obtain results, but the actual details do not matter, as long as they are equal for the three cases.

3.4.2B DATABASE

The next part that is required for this study is a database. A drill-hole database contains information obtained from multiple drill holes, such as rock characteristics, grades, etc., stored in columns with numerous rows, representing sections with equal characteristics of these drill holes. Some key columns that are required for a drill-hole database are the X, Y and Z coordinates, the grade, and the zone definition for example. As mentioned above, this database was obtained via the company Datamine. The company has various "standard" block models at their disposal for training purposes, of which this model is one. This block model describes a gold deposit apt for open pit extraction, which suits the purpose of this study.

The original block model had a size of 7.9M tons and an average grade of 1.85 gr/t Au, which does not correspond with the desired values for the three open pit settings. Therefore some manipulations on the model were done to create a block model with a sufficient size. This model was used to create three new versions, corresponding with the grades of 1.6, 2.9 and 7.5 gr/t that is desired for the three cases. The correct corresponding sizes will be taken from the schedule files that will be created in NPVScheduler, which is less work than manipulating the block model size for all three cases.

Within the block model there are three different types of waste and one ore type, all with various densities (see Table 5 for details).

<div align="center">

TABLE 5. DETAILS OF THE DIFFERENT ZONES OF THE DATABASE

ZONE	DENSITY	LITO
1	2.85	ORE
2	1.8	SOIL
3	2.7	WROCK
4	2.2	SROCK

</div>

3.4.2C IMPORTED MODEL

The next step is to import this block model into NPVScheduler in order to determine the economic model and obtain the ultimate pit limit, pushbacks and schedules for each of the three cases. The general statistics of the imported model can be viewed in Table 6. Note that these statistics are of the medium-sized model, where the size of 24Mt and an average grade of 2.9 gr/t Au is shown. All of the other parameters that are shown are equal for the three different pits, except for the grade. The correct size of the deposit will be adopted from the schedule, which is done a few steps later on.

<div align="center">

TABLE 6. IMPORTED MODEL STATISTICS OF THE MEDIUM-SIZED DEPOSIT, EXTRACTED FROM NPVSCHEDULER

</div>

Model Definition					Global Stats		
Reblocked	No					tonnes	
Density Multiplier	1				Ore	23,933,665	
Cells under Topography	105,124				Waste	957,021,677	
	Block Count	Block Size	Origin		Total	980,955,342	
X	374	20	693,45			Minimum	Maximum
Y	360	20	7,186,075		Density	1,8	2,85
Z	66	10	800		Slope Region	1	4
Rock Type Stats							
	Code	Tonnage	AUgrade	AUgrade Min	AUgrade Max	AUgrade Range	
		tonnes	g/tonne	g/tonne	g/tonne	g/tonne	
ORE	4	23,933,665	2,9	0,1671	25,4184	25,2513	
WROCK	1	451,471,388	0	0	0	0	
SOIL	2	45,407,814	0	0	0	0	
SROCK	3	460,142,476	0	0	0	0	

3.4.2D ECONOMIC MODEL

As described earlier, for all three cases the same economic parameters will be used, to ensure the ultimate pit is created under equal circumstances. After importing the geological model, the first step is to create this economic model and define its parameters (see Table 7). These values are determined based on of other open pit gold mine projects, representing a realistic scenario.

TABLE 7. PARAMETERS USED TO CREATE THE ECONOMIC MODEL

Parameters	Values
Selling Price	$40.00/gr Au
Selling Costs	$0/gr Au
Mining Cost	$5.50/t
Mining Dilution	10%
Mining Recovery	95%
Mining CAF ORE	1.00
Au grade recovery	88%
Processing cost	$18.00/t
Mining CAF WROCK	0.95
Mining CAF SOIL	0.70
Mining CAF SROCK	1.00

Since the economic model is dependent on the average gold grade, the calculated statistics of this model will differ for the three cases. Table 8 shows the statistics of the economic model of the medium-sized deposit case, with an average grade of 2.9 gr/t Au, the other deposits' statistics can be reviewed in the Appendix-B.

TABLE 8. STATISTICS OF THE ECONOMIC MODEL FOR THE MEDIUM-SIZED DEPOSIT

Statistics	Value in million US $
Revenue	2 315
Processing Costs	441
Mining Costs	5 196
Net Value (Revenue – Processing Costs – Mining Costs)	(3 323)
Ore Value	1 704

3.4.2E ULTIMATE PIT

After the economic model is created the next step is to create the ultimate pit limit. Since this limit is dependent on the economic scenario, the ultimate pit will be different for the three cases. Again, some parameters need to be defined, which are shown in Table 9. The only parameter that is different among the three cases is the average output rate, which will be set at a rate accordingly to the deposit

size. The ultimate pit will be created using the maximize cash flow method (Lerchs-Grossman algorithm) and the LG phases will be generated using price factors. As can be seen in the table there are different slopes for certain regions. These regions correspond with the different rock types, and since all rock types have different geological properties, the maximum safe slope angle differs per type.

TABLE 9. PARAMETERS USED FOR THE ULTIMATE PIT CALCULATIONS FOR THE MEDIUM-SIZED DEPOSIT. *OBTAINED BASED ON A LOM OF TEN YEARS

Annual discounting	8%
Average output rate per 365 days	570 000 tons*
Incremental factor	5%
Slope of region 1 (WROCK)	60 degrees
Slope of region 2 (SOIL)	30 degrees
Slope of region 3 (SROCK)	45 degrees
Slope of region 4 (ORE)	60 degrees

The statistics of the ultimate pit calculations (regarding the medium-sized deposit) can be seen in Table 10, the statistics of the other pits can be viewed in Appendix-B. These numbers now represent the maximum amount of extracted material under the current economic circumstances resulting in the highest possible NPV. Note that the software has changed the minimum Au grade to the cutoff grade value, the boundary at which extraction is still profitable, taking the other economic parameters into account.

TABLE 10. ULTIMATE PIT STATISTICS OF THE MEDIUM-SIZED DEPOSIT, EXTRACTED FROM NPVSCHEDULER

Global Stats							
Cash	Revenue	Process Cost	Mining Cost	Net Value	NPV	V3 NPV	Ore Value
	2,197,560,332	408,484,832	324,521,788	1,464,553,712	759,372,277	891,025,888	1,639,797,482
	Block Count	Mass					
ORE	1,233	21,716,365					
Waste	3,903	41,526,420					
Total	5,136	63,242,785					
Strip Ratio	1,9,122						
ORE Stats							
	Mass	AUgrade	AUgrade Min	AUgrade Max	AUgrade R	AUgrade R Min	AUgrade R Max
	tonnes	g	g/tonne	g/tonne	g	g/tonne	g/tonne
ORE	21,716,365	65,716,516	0,6813	14,8974	54,939,009	0,6813	14,8974

3.4.2F PUSHBACKS

Now that the ultimate pit limit has been determined, it is now possible to design the pushbacks. The pushbacks divide the ultimate pit into multiple zones, to which boundaries such as size control can be assigned. It is important to recall that the pushbacks do not necessarily stand for a fixed period of time, but they can be used as a framework for the later schedules. The parameters used for the medium-sized deposit can be seen in Table 11 and the results in Table 12.

TABLE 11. PARAMETERS USED TO CREATE PUSHBACKS FOR THE MEDIUM-SIZED DEPOSIT. "MINIMUM REMANANT IS THE SURFACE AREA BETWEEN ULTIMATE PIT AND PUSHBACK RIMS"

Parameters	Values
Mining width	5 meters
Minimum remnant	40 000 square meters
Size control Total ORE, Pushback 1	570 000 tons
Size control Total ORE, Pushback 2	1 100 000 tons
Size control Total ORE, Pushback 3	2 500 000 tons
Size control Total ORE, Pushback 4	4 000 000 tons

Since the case study will only look at the pit in its ultimate limits, the intermediate steps of the pushbacks will have no influence on the final result. It is necessary to design the pushbacks in order for the program to create the later schedules, but the outcomes can be valued as redundant. They are shown here in order for the reader to understand the process of mine design better, but therefore the results of the other cases will not be implemented in the Appendix.

TABLE 12. PUSHBACK STATISTICS OF THE MEDIUM-SIZED DEPOSIT

Pushback	Rock tons (Mt)	Revenue (million $)	Processing Costs (million $)	Mining Costs (million $)	Ore tons (Mt)
1	3.12	391.08	44.84	16.07	2.39
2	1.75	205.76	21.77	8.79	1.16
3	10.17	582.78	67.87	50.87	3.61
4	0.39	32.76	5.93	2.12	0.32
Total	15.42	1 212.39	140.41	77.66	7.65

3.4.2G SCHEDULE

With the pushbacks in place, it is now possible to create a more detailed, yearly schedule. One of the goals is to keep the ore output and stripping ratio as constant as possible due to equipment allocation. Another is obtaining a high revenue as soon as possible in order to pay back earlier capital expenses.

This is more or less a balancing act where it is not possible to satisfy all desired targets, and therefore concessions have to be made. The parameters used to create the schedule are listed in Table 13 and a part of the statistics can be seen in Table 14. Because the other models have different tonnages and thus different yearly outputs, the values listed below will be different for the three cases. These values can be reviewed in Appendix-B.

TABLE 13. PARAMETERS USED TO CREATE THE SCHEDULE FOR THE MEDIUM-SIZED DEPOSIT

Parameters	Values
Consumption rate total rock	1 423 500 tons / year
Primary objective	Maximize NPV

TABLE 14. SCHEDULE STATISTICS OF THE MEDIUM-SIZED DEPOSIT, EXTRACTED FROM NPVSCHEDULER

Year	Rock	Revenue	Processing Cost	Mining Cost	Capital Costs	NPV	ORE	ORE (w)	WROCK	SOIL	SROCK	AUgrade	AUgrade R
	tonnes	$	$	$	$	$	tonnes	tonnes	tonnes	tonnes	tonnes	g	g
1	1,443,688	144,556,919	17,752,732	7,126,784	0,0000	114,845,231	943,792	0,0000	3,038	492,525	4,333	4,322,874	3,613,923
2	1,437,027	224,302,745	23,475,497	7,648,899	0,0000	170,496,586	1,248,033	3,741	32,991	148,894	3,369	6,707,618	5,607,569
3	1,412,934	156,053,236	15,171,205	6,931,952	0,0000	108,074,964	806,550	5,700	109,266	490,387	1,031	4,666,663	3,901,331
4	1,403,539	100,249,722	15,282,270	6,866,053	0,0000	59,549,404	812,454	0,0000	32,737	511,763	46,584	2,997,898	2,506,244
5	1,420,369	270,979	20,103	5,474,824	0,0000	(3,648,161)	1,069	0,0000	3,375	1,415,925	0,0000	8,103	6,774
6	1,427,738	5,480,556	552,838	6,705,788	0,0000	(1,147,263)	29,391	0,0000	844,003	554,344	0,0000	163,892	137,014
7	1,425,980	54,632,000	5,540,103	7,483,217	0,0000	24,214,827	294,530	178,1250	1,095,947	35,325	0,0000	1,633,732	1,365,800
8	1,422,605	122,259,910	12,981,633	7,622,899	0,0000	55,621,376	690,145	0,0000	732,459	0,0000	0,0000	3,656,098	3,056,498
9	1,418,270	126,906,018	17,062,580	7,661,825	0,0000	51,361,171	907,101	0,0000	504,225	0,0000	6,944	3,795,036	3,172,650
10	1,432,178	133,327,575	16,253,427	7,722,493	0,0000	50,699,372	864,084	0,0000	561,769	0,0000	6,325	3,987,069	3,333,189
11	1,178,241	144,348,271	16,313,737	6,418,974	0,0000	52,814,652	867,291	0,0000	223,088	0,0000	87,863	4,316,635	3,608,707
Total	15,422,568	1,212,387,931	140,406,126	77,663,708	0,0000	682,882,160	7,464,440	9,619	4,142,897	3,649,163	156,449	36,255,619	30,309,699

In Table 14, it can be clearly seen that the program tries to honor the given constraints of 1 423 500 tons of total rock per year and to maximize NPV. Since the total model is much larger compared to the desired deposit sizes, the choice was made to create the pushbacks and schedules based on an LG pit phase instead of the ultimate pit. This ensures that not the entire deposit is taken into account when creating the schedules. Else, this would result in a pit of just one or two benches deep, but covering a very large surface area, which is not ideal for pit modeling, nor is it realistic. Regarding the medium-sized deposit, pit shell number 6 was used, this shell contains 7.5Mt of ore, which is sufficient compared to the desired size of 5.7Mt. The pit shell number that is used will be different for each deposit size.

For the three cases, the choice was made to honor a stable total output in order to create the most stable schedule. This results in a slightly fluctuating ore output, but this can be solved with for example stockpiles, of which the full details can be reviewed in Appendix-B. Again, regarding the objective of the case study, this is a choice that has no impact on the final results, but the reasoning behind it is explained to give the reader a better understanding of the entire process.

What is discussed in the section "pushbacks" is also applicable to the schedule. In this case, the only thing that is looked at is the ultimate pit, so all the yearly schedules to reach those limits will not be used for the analysis of the final results. The only thing the schedule is used for is to determine at which year the targeted production for the three cases is met. Once this is known, the schedule file of that year will act as the ultimate pit for each respective pit size and can then be exported to StudioOP for the actual pit and haul road design. The actual calculated tonnages and the obtained NPV of the three projects are listed in Table 15. The full details can be found in Appendix-B.

Using the schedule files instead of the ultimate pit file is necessary because the grades of the model have been altered to correspond with the desired three cases, but the size of the entire deposit is still 24Mt. Therefore simply taking the ultimate pit limit will result in an incorrect pit when related to the required sizes of 0.77Mt, 5.7Mt, and 13Mt. As stated earlier, the process of using the schedule files instead of creating a block model with the correct size is simply a matter of time-saving.

TABLE 15. CALCULATED STATISTICS FOR THE THREE CASES IN NPVSCHEDULER

Parameters	Small Pit	Medium Pit	Large Pit
Theoretical max. NPV	419 million US $	579 million US $	323 million US $
Total Tonnage	1.33Mt	12.81Mt	30.63Mt
Total Ore Tonnage	0.86Mt	5.73Mt	13.48Mt

When examining the values that are obtained a few things must be noted. First, all the values obtained from NPVScheduler are theoretical, meaning that they will change once the actual design in StudioOP is made. This is due to for example the smoothing of curves in the pit, which is not yet done in NPVScheduler. Next, the desired tonnages for the three deposits are not exactly as they were desired. This is due to the fact that the ultimate pits are extracted via the schedule files, which are based on the entered consumption rates. Therefore the deposit sizes are slightly larger than intended. However, this has no impact on the intended calculations of the case study.

What can also be observed, is the fact that the NPV of the small pit is higher than that of the large pit, where much more material is extracted, which might seem contradictory. This can be explained by the fact that the grade distribution, but not the grade of the deposits is equal. Since the small deposit has a grade of 7.5 gr/t compared to 1.6 gr/t for the large deposit, the small deposit will yield a much higher revenue per ton of ore. Besides this, the effect of the discount rate has an impact on this as well, since the smaller pit has a shorter LOM than the large pit, the revenue that is obtained will not be discounted as much, resulting in a higher NPV.

3.4.3 STUDIOOP AND FPC

With the desired results obtained from NPVScheduler, it is now possible to export the correct schedule files to StudioOP, the program in which the actual "designing" of the mine will take place. Making the design involves a lot of different steps that cannot be generally described but involve experience with the program, therefore these processes will not be explained in full detail here. The main goal in this sub-section is to show the final design of the pits and highlight some of the characteristics and parameters.

From the obtained results in StudioOP, calculations in FPC can be made to come to the eventual results; different fleet selections and haul road designs. The process described below is chronologically and since information from both programs is needed to come to each new step, there will often be a switch from StudioOP to FPC and vice versa.

3.4.3A INITIAL MINE DESIGNS

The first step is to create the initial designs in StudioOP. For this, the exported schedule files will mainly be used. The three block models of the respective deposits with their corresponding grades are used for guiding, to ensure that the design does not exceed the limits of the block model. These initial designs can be seen in Figure 20. The designs were made with an initial bench height of 10 meters, based on the block height, but can be changed accordingly in a later stage.
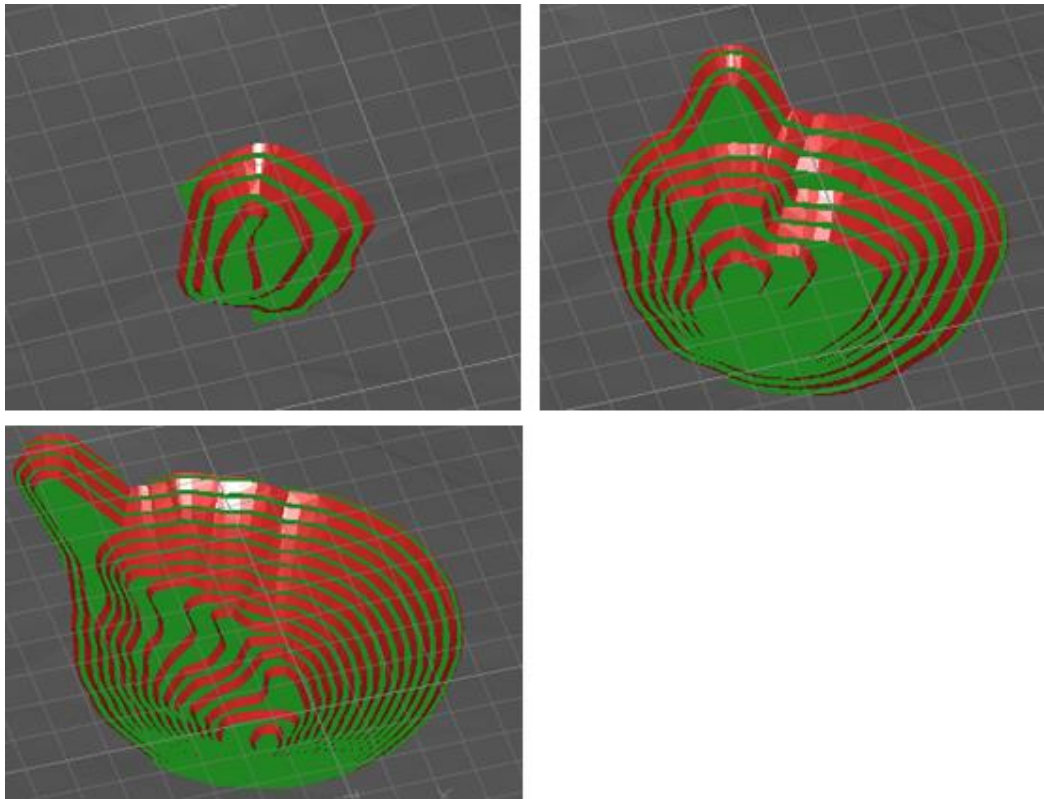
FIGURE 20. THE INITIAL DESIGNS WITH ON THE TOP LEFT THE SMALL PIT, TOP RIGHT MIDDLE, AND BOTTOM LEFT LARGE PIT. 1 SQUARE REPRESENTS AN AREA OF 50X50M

The goal of these initial designs is to create initial haul road profiles accordingly, and from these designs obtain the haul road length required for the different pits. This is necessary in order to determine a fleet selection with FPC later on, where the haul road length is one of the required parameters. To obtain these lengths in StudioOP, a string file is used as a measuring tool.

3.4.3B INITIAL HAUL ROAD DESIGNS

Initially, for each pit, three designs were made with haul road widths of 10, 20 and 30 meters as arbitrary values, which are only used for the purpose of determining the haul road lengths. These values were determined by the experience of a mine design engineer from Datamine, and are roughly based on the block size of the model. Multiple widths were chosen because changing the haul road width will affect the design, and thus also the haul road length, which can be seen in Figure 21. From these three designs, the average haul road lengths were calculated and the results are shown in Table 16. Note that these lengths are the in pit length, from the bottom to the pit rim. The results of the other pits can be examined in Appendix-C.

Haul road width (meters)	Small pit haul road length (meters)	Medium pit haul road length (meters)	Large pit haul road length (meters)
10	290	830	1575
20	300	867	1630
30	310	905	1630
Rounded Avg.	300	870	1610

FIGURE 21. ROAD WIDTHS OF 10 (TOP LEFT), 20 (TOP RIGHT) AND 30 METERS (BOTTOM LEFT) FOR THE MEDIUM PIT

When examining Figure 21 closely, it can be observed that the design changes once the haul road gets wider, since the design has to accommodate for more haul road space. Especially in the bottom left and the top right section of the deposit the changes are notable. This already illustrates the general concept of this case study, what remains is determining the precise haul road widths using FPC and calculating the differences between the designs.

3.4.3C INITIAL FLEET DETERMINATION

Now, with an average estimated haul road length obtained from StudioOP and the daily/ yearly production known (see Table 17), it is possible to determine an "initial fleet", which will be referred to as the base case or medium sized fleet.

TABLE 17. INITIAL HAUL ROAD WIDTHS AND THE CORRESPONDING LENGTHS OF THE DIFFERENT PITS

Haul road width (meters)	Small pit haul road length (meters)	Medium pit haul road length (meters)	Large pit haul road length (meters)
10	290	830	1575
20	300	867	1630
30	310	905	1630
Rounded Avg.	300	870	1610
Yearly production	438 000 metric tons	1 423 500 metric tons	2 299 500 metric tons

Besides the production rate and haul road length, other factors also govern a suitable equipment selection. These are for example the density of the material, the operating hours and the rolling resistance. The density of the material, which is discussed at the beginning of the case study, will impact the size of the loading tool's bucket and therefore affect the equipment's production rate. The other factors will be explained in more detail below.

3.4.3D TIME USAGE MODEL

The operating hours dictate the number of hours per year the equipment could be operating, which directly impacts the production. However, the operating hours that are available are not equal to the scheduled hours, or the hours that the equipment is actually operating. This is displayed in Figure 22, which shows the time usage model for this case study with an explanation regarding these values below the figure.
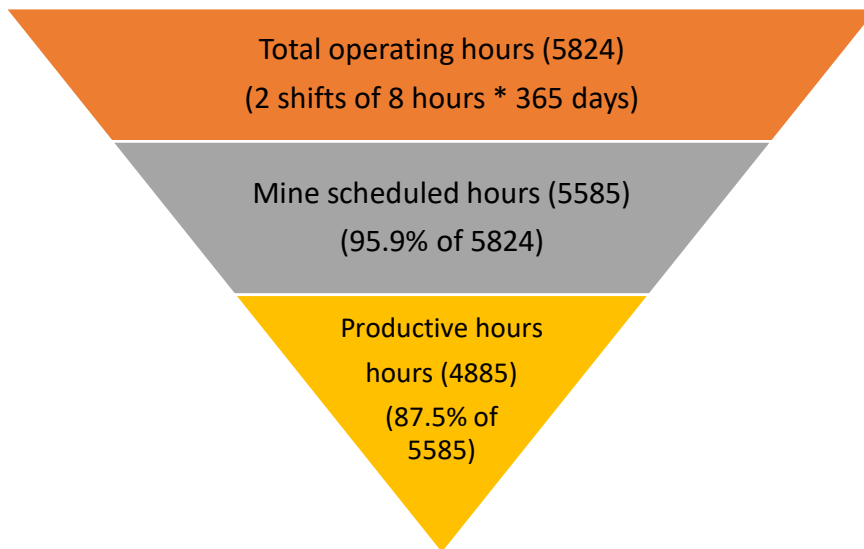
FIGURE 22. TIME USAGE MODEL USED IN THE CASE STUDY

Regarding the operating hours, a schedule of two shifts of 8 hours per day is used. The choice for not using three shifts is because the deposits can be seen as relatively small deposits, where it is not common to use more than two shifts per day (Caterpillar 2017). The Mine scheduled hours result from the downtime caused by holidays and weather conditions, which is set at 4.1% of the operating hours (Caterpillar 2017). What remains after that is the Machine scheduled hours, consuming 12.5% of the Mine scheduled hours (Caterpillar 2017) and is caused by shift changes, lunch & meetings, and scheduled downtime. What remains are the productive hours, the effective time that the machines are actually operating.

3.4.3E EFFICIENCIES

Besides these losses in time described above, there are additional losses resulting from unscheduled downtime, non-production time and job efficiency factors. These factors are entered in FPC, where the program translates these losses in decreased hourly production, instead of a reduction of available hours. The values that are used for this are displayed in Table 18 and are according to Caterpillar's standards. These values are very-site specific and can, therefore, be different in other scenarios.

TABLE 18. EFFICIENCIES USED IN THE CASE STUDY

Parameters	Values
Operator Efficiency	90%
Hauler availability	90%
Loader availability	90%
Fleet availability	Variable (hauler availability*loader availability)

3.4.3F ROLLING RESISTANCE

For the different pits, a haul road grade of 8% percent was used, as was suggested in the literature review. Besides this haul road grade, the nominal rolling resistance should be taken into account as well. This is the resistance the truck faces due to the subsurface it is riding on. According to Caterpillar, in areas that cannot be perfectly maintained such as the load and dump area, a rolling resistance of 3% is common, on well-maintained haul road sections the rolling resistance is 2%, depending on the circumstances. The combination of the two results in the total effective grade, which is calculated by FPC and is used to calculate the truck's performance.

3.4.3G ACTUAL FLEET SELECTION

With this information in mind it is possible to determine a suitable initial fleet for the three deposits and from there select alternative fleets, creating a smaller and a larger equipment size fleet scenario per operation. The loading tool is always the initial part of equipment that is chosen, since this will govern the production rate, and based on that the haulers are determined. The selections and the associated truck widths are listed in Table 19. Besides this, the required haul road width is calculated, based on the literature review, at 4 times the truck's width.

TABLE 19. FLEET SELECTION FOR THE DIFFERENT DEPOSITS

Scenario	Equipment	Small pit	Medium pit	Large pit
Small fleet	Loading	1* 446 Backhoe loader	1* 962G Wheel loader	1* 962H Wheel loader
	Hauling	Hypothetical	5* D20D Articulated	7* 725 Articulated
	Truck width	2 315mm	2 726mm	2 877mm
	Haul road width	9 260mm (9.3m)	10 904mm (10.9m)	11 508mm (11.5m)
Medium (initial) fleet	Loading	1* 446 Backhoe loader	1* 962G Wheel loader	1* 962H Wheel loader
	Hauling	2* D20D Articulated	4*725 Articulated	6* 735 Articulated
	Truck width	2 726mm	2877mm	3 353mm
	Haul road width	10 904mm (10.9m)	11 508mm (11.5m)	13 412mm (13.4m)
Large fleet	Loading	1* 446 Backhoe loader	1* 962G Wheel loader	1* 962H Wheel loader
	Hauling	1* 725 Articulated	3* 735 Articulated	5* 771D Off-Highway
	Truck width	2 877mm	3 353mm	3 659mm
	Haul road width	11 508mm (11.5m)	13 412mm (13.4m)	14 636mm (14.6m)

As can be seen in the table, the width of the intended haul roads is rounded to a precision of 10cm. This was done because in practice it is not realistic to construct a haul road within the accuracy level of several centimeters.

The truck selection for both the large and medium pit correspond with realistic scenarios. However, when concerning the small pit fleet scenarios, the tonnage that has to be moved is so small that Caterpillar does not have mining trucks of a suitable size for this work. The result is that the amount of trucks per scenario is very low, and for the small fleet scenario there is even no actual hauler that suits the production rate. For this case, the average of the size jumps in truck model width is used to determine a hypothetical truck with a "realistic" width. The choice for this approach is based on the fact that the only desired value from this fleet selection process is the truck width, which is necessary to calculate the haul road width. Additionally, the small size of the deposit results in the fact that unrealistic loading equipment regarding mining operations is used in the small pit scenario, such as a backhoe loader.

These issues illustrate the problems that were expected and explained at the beginning of this chapter related to the small deposit sizes. Due to the lack of workable data, it was not possible to create larger deposits. This resulted in pits that were considered very small, causing doubts on their usefulness. Since no other options were available, the decision was made to proceed with these pit sizes anyway to see if these doubts would be confirmed at the fleet selection step. From these results, it can be concluded that the small pit scenario is not suitable for Caterpillar's equipment. Therefore it is valued too small for some of the purposes of this thesis, such as fleet selection comparison. However, as described above, some of the obtained results from the small pit scenario can still be used as a comparison with the medium and large pit scenario. This will be further explained in the analysis chapter.

3.4.3H ACTUAL HAUL ROAD DESIGNS

Now that the desired road widths are known from the fleet selections, which were made in FPC, it is possible to create the pit designs with the desired road widths. The results for the medium-sized deposit can be seen in Figure 23. The actual results on the design will be made clear via the in-pit calculations. The results on the other pits can be examined in Appendix-C.
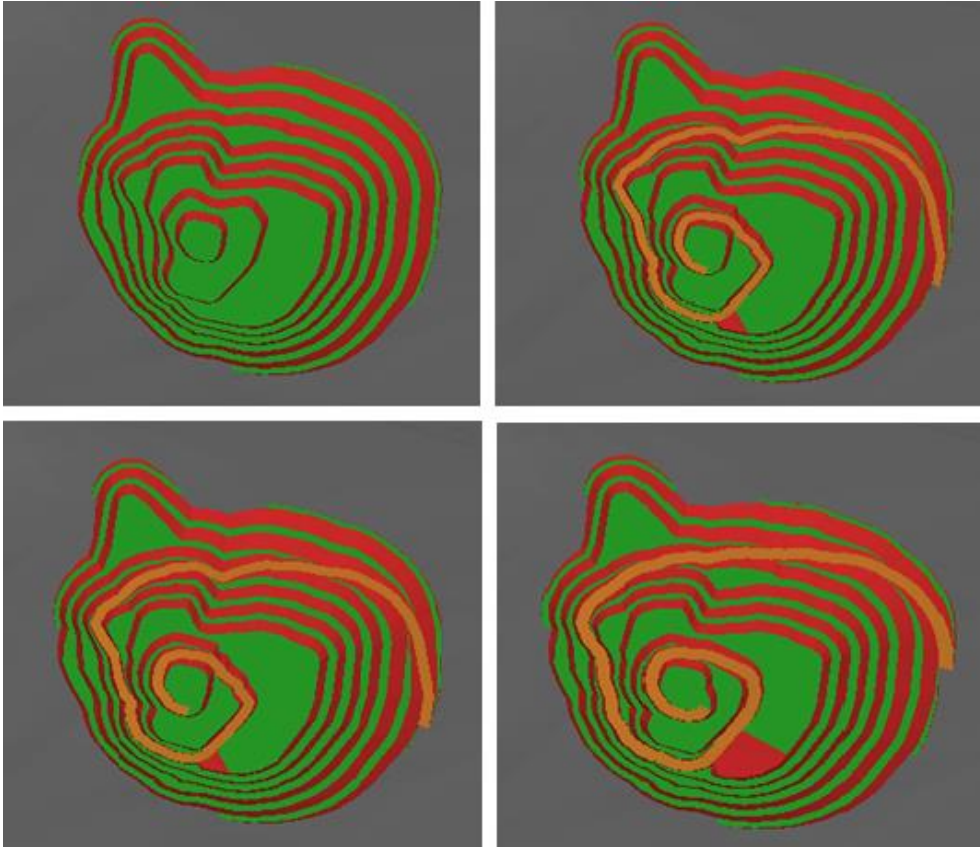
FIGURE 23. ACTUAL HAUL ROAD DESIGNS FOR THE MEDIUM PIT. TOP LEFT NO ROAD, TOP RIGHT SMALL, BOTTOM LEFT MEDIUM AND BOTTOM RIGHT LARGE HAUL ROAD DESIGN

3.4.3I CALCULATED RESULTS

With the desired haul road designs implemented in the mine design, the effect these changes in width have can now be calculated. StudioOP has a function that lets the user calculate the entire in-pit volume and tonnage per lithological zone, as well as the average grade of the material present. This function will be used to determine these changes, and the obtained results are listed below in Table 20.

Scenario's, all roads have 8% grade, unless stated otherwise	Tonnage in Mt	Absolute difference with initial scenario. Tonnage in Kt	Percentage difference with initial scenario. Tonnage	Average Au Grade. gr/t	Absoute difference with initial scenario. Grade gr/t	Percentage difference with initial scenario. Grade
Large pit, no road	28,85	-779,11	-2,63%	2,108	0,037	1,81%
Large pit, small road width (11,5m)	29,47	-159,64	-0,54%	2,078	0,007	0,36%
Large pit, medium road width (13,4m)	29,63	0	0,00%	2,070	0,000	0,00%
Large pit, large road width (14,6m)	29,76	128,98	0,44%	2,063	-0,008	-0,36%
Medium pit, no road	12,07	-332,02	-2,68%	5,273	0,186	3,65%
Medium pit, small road width (9,9m)	12,3	-110,03	-0,89%	5,136	0,049	0,96%
Medium pit, medium road width (11,5m)	12,41	0	0,00%	5,087	0,000	0,00%
Medium pit, large road width (13,4m)	12,48	71,09	0,57%	5,060	-0,028	-0,54%
Small pit, no road	1,8	-65,42	-3,51%	16,430	0,182	1,12%
Small pit, small road width (8,5m)	1,84	-22,76	-1,22%	16,375	0,127	0,78%
Small pit, medium road width (9,9m)	1,86	0	0,00%	16,248	0,000	0,00%
Small pit, large road width (11,5m)	1,91	44,14	2,37%	16,285	0,036	0,22%
Large pit, medium road width (13,4m), 6% grade	29,75	115,35	0,39%	2,074	0,004	0,18%
Large pit, medium road width (13,4m), 8% grade	29,63	0	0,00%	2,070	0,000	0,00%
Large pit, medium road width (13,4m), 10% grade	29,46	-177,28	-0,60%	2,082	0,012	0,56%

In this table, only the total tonnages and the Au grade are shown, since these are the most interesting factors. The different scenarios are compared to the "initial" base case scenario, which is for each pit the medium road width scenario shown in light blue. Additionally, the statistics of the pit without roads is shown to illustrate the impact a haul road has in general on the mine design itself. The results in this table will further be discussed in the following chapter.

4 ANALYSIS

Regarding the analysis of the results, a few notes must be made in advance for clarification. First, some of the pits that were used for this study are concerned to be unrealistically small operations, which has been addressed in the previous chapter. This has implications on the life of mine of the project, which is, with the calculated production rates also relatively short. These short LOMs do not justify the choice for making the investment regarding the purchase of an equipment fleet, so for the exploitation of such as deposit a hired fleet would be required.

This is an indication that, as mentioned before, some of the deposits are not of a sufficient size to reflect a realistic mining operation with the incorporation of Caterpillar's equipment, leading to doubtful results in some cases. Unfortunately, because of the earlier addressed problems related to data acquisition, these pit sizes were the only possible option. On the other hand, some of the results, such as the impact of narrowing or widening a haul road on a mine design, can still be used, regardless of the deposit size. This will be further explained in the following sections.

Besides these issues, the additional construction and maintenance costs related to different fleets and thus haul road layouts are not discussed in the case study. The reason behind this choice is that these factors are very much site-specific, and will vary for each project. Making assumptions on these costs related to the case study is based on assumptions, and will therefore not improve the results of the study. Also a detailed analysis regarding the cost related to the purchase of a fleet compared to a hired fleet is not included in the scope of the case study. However, general statements regarding the increase or decrease of these costs related to different mine design scenarios will be given in order to create a clearer view of the pros and cons of different scenarios.

4.1   EFFECT OF CHANGING HAUL ROAD WIDTH ON MINE DESIGN

From the fleet selections in Table 19 and the results in Table 20, it is clear that increasing the haul road width results in an increase of pit geometries (surface area) for each pit, and vice versa for a decreasing width. The increase in total tonnage ranges from 2.37% to 0.44% compared to the base cases for the small and large pit respectively. This can be explained by a decrease in the overall pit angle, necessary to accommodate wider haul roads. The result is an extra amount of material that has to be moved, and generally a decrease of the average Au grade in the pit as well, compared to the initial scenarios stated in blue.

The only outlier concerning this change of Au Grade is the "Small pit with large road" design, which has an increase in average Au grade of 0.22% compared to the base case. This can be explained by the fact that the average Au grade is dependent on the grade distribution within the block model. A smaller deposit is in this case more susceptible regarding a small change, which will have a higher influence on the average grade compared to a larger deposit. So, in this case, the extra material that needs to be removed to accommodate the large haul road turns out to be in a (slightly) higher ore grade section, resulting in an average increase where a decrease would have been expected.
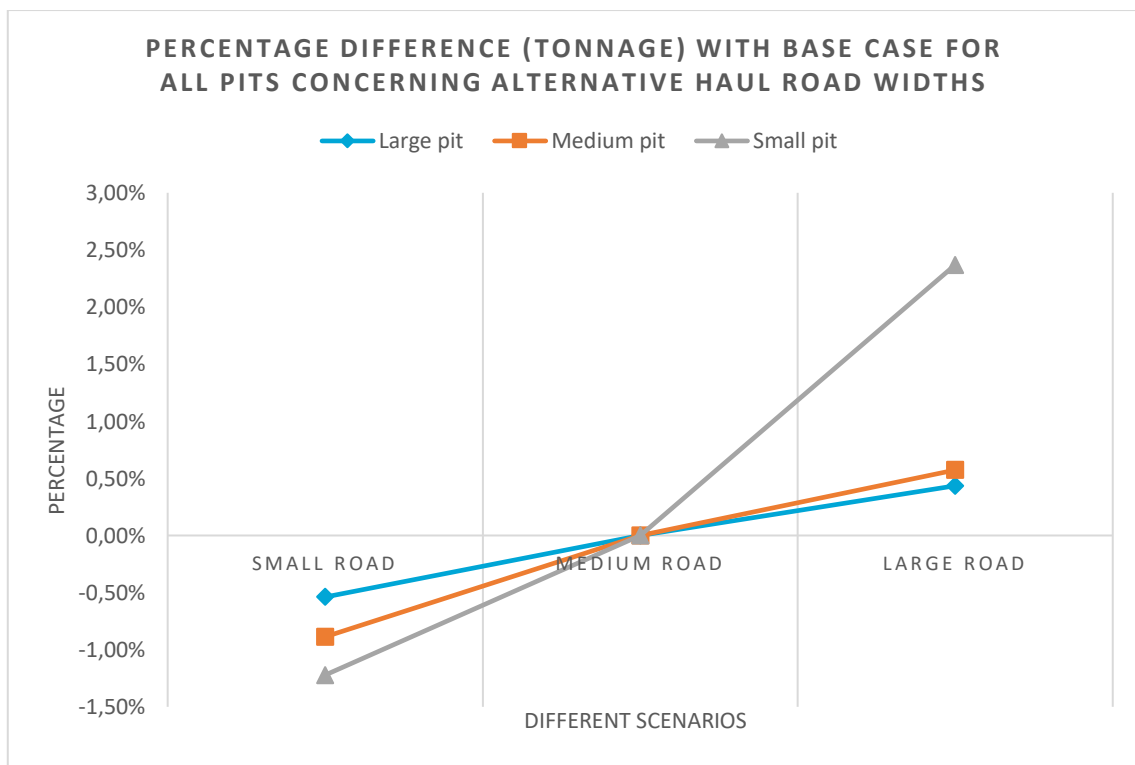
FIGURE 24. PERCENTAGE DIFFERENCE (TONNAGE) WITH BASE CASE FOR ALL PITS CONCERNING ALTERNATIVE HAUL ROAD WIDTHS

When examining Figure 24, where the percentage difference compared to the base case for each pit is shown in a graph, it can be seen that as the deposit size increases, the effect in terms of percentage on the tonnage decreases. This is expected and can be explained by the fact that the change of haul road width is in terms of percentage proportionally much lower than the change in tonnage per deposit.

Also, there is a difference in percentage regarding the small and medium road, compared to the medium and large road. Especially regarding the medium and large pit, the numbers deviate more from the base case with the small road scenario (-0.89% and -0.54% respectively) than with the large road scenario (0.57% and 0.44% respectively). This can be explained by the fact that the road width does not increase gradually, but proportionally to a truck's width. The jump in truck width when switching from a small to a large truck is, in this case, larger compared to the jump from a medium to a large truck, which causes the increased percentage.

These results prove the general statement of the investigation, and besides, give additional evidence that a larger equipment size is not necessarily more profitable. Concerns regarding for example flexibility, dilution and a loss of production have already been described in the literature review by Dunbar, Desserault and Scoble (1999), Gilewicz (2002) and Gajigo and Dhaou (2015). Next to these concerns, the results show that an increase in equipment size will lead to a (significantly) more negative economic scenario regarding pit geometries and thus stripping ratio. Therefore the use of larger equipment should be carefully investigated prior to the start of operations.

Since trucks exist with a different width, but equal theoretical production, this is something to look at in further studies, where the highest production per meter of truck width would be preferable.

Since the ultimate pit is designed and based on the given economic scenario, exceeding these boundaries will always result in a decrease of NPV for each project, even if this might concern a slight increase in average Au grade. Therefore, when solely looking at haul road width related to the project's economic scenario, smaller haul roads would be preferred. On the contrary, changing the truck size will also influence the production rate, the Capex and the Opex. The effects on these aspects will be described in the discussion chapter.

4.2 EFFECT OF CHANGING HAUL ROAD GRADE ON MINE DESIGN

Figure 25, which depicts the impact of a changing haul road grade on the total tonnage of the large pit, illustrates that with an increasing haul road grade, the total tonnage of both ore and waste of the deposit decreases. There is an increase of 0.4% in tonnage for a haul road grade of 6%, and a decrease in total tonnage of 0.6% for a haul road with a 10% grade, where the 8% haul road grade was used as a reference.
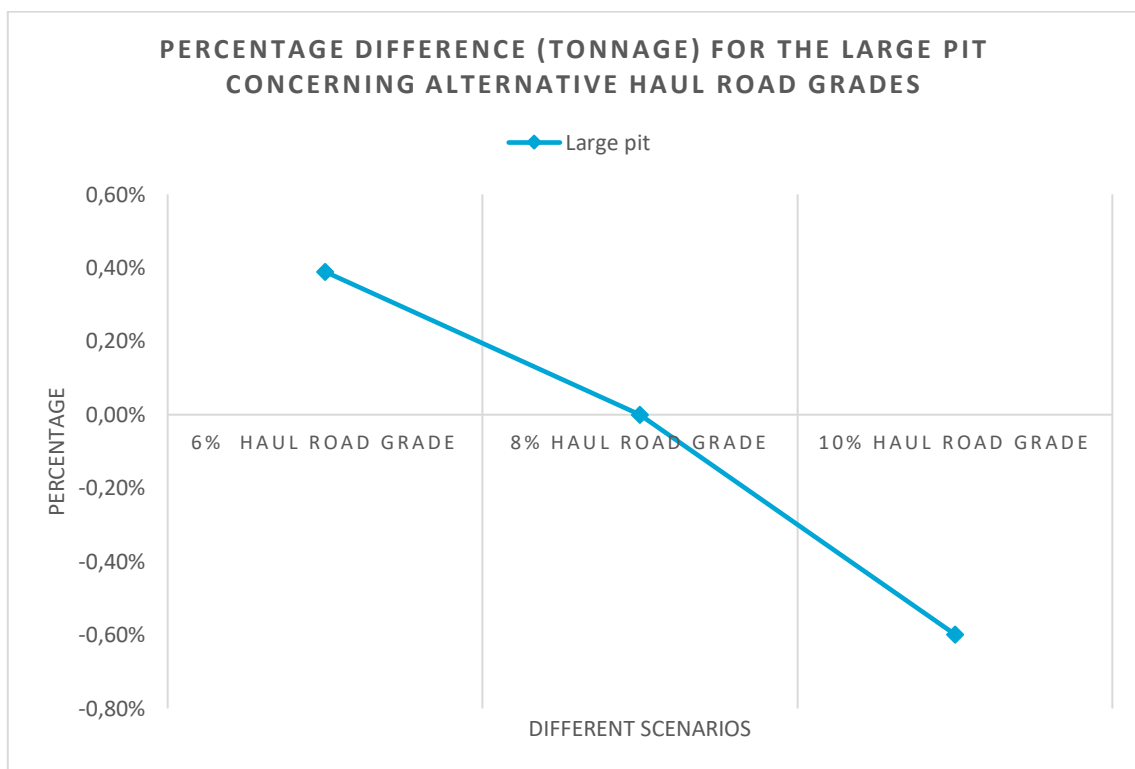
FIGURE 25. PERCENTAGE DIFFERENCE (TONNAGE) FOR THE LARGE PIT CONCERNING ALTERNATIVE HAUL ROAD GRADES

This can be expected since the haul road grade impacts the length of the haul road and also impacts the overall pit angle. Increasing the grade will result in a shorter road and a steeper possible pit angle, and thus a lower stripping ratio and total tonnage. This shows that, in addition to what Tannant and Regensburg (2001) and Masabattula (2011) have stated in the literature review, the optimum grade of a haul road is dependent on both the truck's performance and the economic impact it has on the mine design.

Since the different haul road grades are only investigated on the large pit, the results for other deposit sizes will have to be extrapolated. Using the results from the previous section regarding the haul road widths, it is expected that changes in haul road grade will follow the same pattern. This can be explained by the fact that an increase in haul road grade has the same effect on the mine design as increasing the width; an increase in stripping ratio. With increasing pit geometries the effect of alternative haul road grades in terms of percentage will decrease and vice versa for smaller deposits.

Therefore, when only taking the haul road grade in mind concerning the project's economic scenario, a higher grade would be preferred over a lower grade.

4.3   Impact of Changing Haul Road Grade on Truck's Performance

From the results regarding the effect of different grades on the mine design, it can be concluded that an increase of haul road grade has a positive effect on the stripping ratio, i.e. lowering it compared to the base case. However, a downside to increasing the haul road grade is the truck's performance that will deteriorate due to the increased effective resistance it has to overcome.

This will not only have a negative impact on the cycle times of the haul trucks, but it will also lower the truck's life expectancy. Because of this fact, maintenance costs of the trucks will increase and scheduled as well as unscheduled downtime will increase, and as Gölbaşi and Dagdelen (2017) have described, this is a significant cost post.

All these factors do not impact the production rate positively and will result in an increase of cost per ton. The exact impact this increase of grade has on the equipment has to be determined for each site individually, since the severity of the impact is also dependent on the type of hauler that is used and the quality (level of maintenance) of the haul road itself. Once this is determined, it might be possible to make a decision on the best site-specific haul road grade.

It is the expectation that, especially with more extensive deposits that run over tens of years, the benefits regarding steeper haul roads outweigh the drawbacks. However, more studies on the impact on the truck's performance are recommended to come to a sound conclusion.

4.4 CAPEX AND OPEX RELATED TO EQUIPMENT SIZE

From the previous sections, it can be concluded that narrower haul roads with a high grade would be preferable regarding the deposits' economic scenario. These preliminary conclusions also have an impact on the Capex and Opex of the project however, which needs to be discussed as well to be able to come to a sound conclusion.

A narrower haul road scenario would result in a smaller equipment size fleet, as can be seen in Table 19 regarding fleet selections for the different pits. Smaller equipment size means a lower Capex related to the purchase, but more equipment is required to meet the same production targets. In the case study, of which all deposits can be regarded as very small in size, this already results in two extra haulage trucks when comparing the large with the small equipment size scenario.

Besides this, the operating costs will be higher for a smaller equipment size. This can be explained by the increase in the number of trucks. Therefore, more fuel will be consumed and also additional truck operators are required, which is especially in more developed countries, with higher wages, a large cost post. Next to this, additional buildings and personnel are required to accommodate the maintenance of the trucks. Combining all these factors will result in a higher cost per ton for small equipment compared to large equipment. The exact difference between the two, however, is dependent on multiple variables, which have to be assessed for each site specifically.

With the increasing level of technological possibilities, some of these negative cost factors that are linked to smaller equipment can be reduced or even eliminated. For example, truck operators could be replaced by Autonomous Haulage Systems (AHS), resulting in not only a more profitable, but also a safer operation. This option will be further examined in the discussion chapter.

4.5   CONSTRUCTION AND MAINTENANCE COSTS OF HAUL ROADS

Changing the haul road characteristics not only impacts the mine design and the truck's performance, but it also influences the costs related to construction and maintenance of those roads. These impacts will not be discussed in great detail here since they are outside the scope of the project. However, it is important to identify all the factors that will be affected due to changes in the haul road layout, in order to be able to get a clear overview of the general problem.

In general, with increasing haul road width, the construction and also the maintenance costs will increase, simply because there is more surface area that needs to be constructed and maintained. The exact increase of these costs is very hard to determine and also dependent on local variables, but it is something to take into account when considering narrower or wider haul roads.

Besides this, an increase in haul road grade will have an impact on these costs. On one side, the construction costs will decrease with an increasing haul road grade, caused by a shorter length of road that needs to be constructed. On the other hand, maintenance costs will increase, since steeper haul roads undergo more wear and are more vulnerable to, for example, erosion caused by rainfall. Besides, with increasing maintenance, the downtime of haulage equipment will increase, affecting the production rate and thus the costs per ton. These factors can vary very much from site to site, and therefore a local assessment has to be made to come to a sound conclusion on the optimal scenario.

4.6   COMBINATION OF RESULTS

When combining the results and keeping the impact that the different haul road designs have on various aspects in mind, the following statements can be made:

- The implementation of any haul road has an extensive impact on the pit geometries and the stripping ratio. This is a known general fact, however actual numbers on this matter are scarce. An increased total tonnage of 2.5% or more is a conservative amount for all deposit sizes that were investigated. The expectancy is that this number will decrease slightly with larger deposits, but will remain in the same range, since generally larger deposits will also require wider haul roads. Since this is a significant impact on a projects value, extensive investigation regarding the most optimal equipment selection/ haul road size combination could be very beneficial for a project.

- An increase in haul road width will result in an increase of total tonnage for all deposits, ranging from 2.37% to 0.44% compared to the base case for the small and large pit respectively. The increase in terms of percentage is expected to further decrease (slightly) with increasing pit geometries, as this trend can be observed from the obtained results.

- An increase in haul road grade will result in a decrease of total tonnage, where the increase in terms of percentage is expected to decrease with increasing pit geometries. For a haul road grade of 6% there was an increase of 0.4% in terms of tonnage, and for a road of 10% there was a decrease of 0.6%, where the 8% road grade was used as a reference.

- An increase in haul road grades will affect the truck's performance and therefore influence the Capex and Opex negatively.

- Increasing the equipment size will result in a lower number of trucks but generally a higher Capex. The Opex will, under normal circumstances, decrease with increasing equipment sizes.

- Increasing the haul road width will increase the construction and maintenance costs. Increasing the haul road grade will result in a decrease in construction costs but a rise in maintenance costs.

5   EVALUATION

Now that the results from the case study have been obtained and analyzed, the research questions can be reflected. The first four research questions and their answers will be discussed below. Besides this, a flowchart will be discussed, showing how the results of the combined research questions can possibly be used in the future. The last research question, regarding an autonomous versus a manned fleet, will be answered in the discussion chapter since it will encompass a theoretical analysis based on the results obtained in the case study.

- What stages of mine design development are there and what tools are used for each stage?

Looking back at the literature review it can be stated that the two major steps of mine design development are mine design and mine planning, including all their sub-stages such as obtaining the database, ultimate pit creation etc. Also, the external factors and equipment selection play a very important role to eventually come to the final mine design, which is a very site-specific result. The designing of a mine can be done with various software packages and tools, of which some are Datamine, Surpac, Whittle or Vulcan. For this study, the NPVScheduler tool was used for the initial design part and StudioOP for the detailed design and planning.

- At which stage of the design process can FPC be integrated?

The combination of the literature review and the practical experiences gained from the case study show that the best stage to implement FPC is at the mine planning stage, at the step where the haul roads are being designed and implemented. In the case study, this was the part where the results from FPC were used to create multiple haul road scenarios. At this stage, there is room to investigate different haul road characteristics, such as width and grade (and thus fleet sizes), and the impact that they have on the mine design with relatively low effort. Subsequently, the production costs of the different fleets can be calculated in FPC, and combining the results make it possible to design a (more) optimal solution.

- What parameters does FPC require to make an optimum fleet selection?

In order to make an optimum fleet selection with FPC the parameters: anticipated production rate, haul road length, grade and equipment characteristics are required. The approximate haul road length

can be extracted from the mine design software, in this case StudioOP. The grade and equipment selection are the parameters that can be changed accordingly to investigate different scenarios.

- What are the consequences of changes in haul road width, gradient and switchbacks for the mine design in an economic perspective?

Increasing the haul road widths will result in a significant increase (±0.5%) of the total tonnage (ore and waste combined) and thus the stripping ratio. However, the increase is dependent on the actual "jump" in haul road width, which is related to the haul truck's size. In terms of percentage, this number will decrease slightly with increasing deposit geometries but it will still play a significant role, especially due to the increase in geometry.

The increase of haul road grade shows similar effects on the total tonnage. Switchbacks are sometimes necessary to maintain the preferred haul road grade, for example, to ensure that the haul road is located in the area with the best geotechnical properties. In these cases, they can ensure a decrease in haul road distance and an increase in overall haul road grade. However, if these circumstances do not occur, they are preferably avoided since they have a significant negative impact on the pit geometries and thus the stripping ratio. Also, they actually increase the travel distance due to the fact that the switchback itself has to be at a lower-or zero grade compared to normal haul road section.

Figure 26 illustrates which steps are required in order to produce a mine design, while integrating fleet selection trough FPC, in order to come to an optimal solution. The actions taken until step five are no different from what is done with a traditional mine design. At this stage, different haulage scenarios will be developed with FPC, and the required haul road characteristics will be used to create multiple designs. When comparing these designs, the operator can make the decision which fleet and associated mine design is preferable for that specific case. These haul road characteristics are then adopted and the design can be finalized.

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┌─────────────────────┐      ┌─────────────────────┐      ┌─────────────────────┐
│                     │      │ Gather information  │      │                     │
│    Investigate      │      │ and develop rough   │      │                     │
│ (site specific)     │ ──▶  │ idea of size, shape │ ──▶  │ Mine Design,        │
│ external factors    │      │ etc. in order to use│      │ including all its   │
│                     │      │ sensible values for │      │ sub-stages          │
│                     │      │ the parameters in   │      │                     │
│                     │      │ mine design and     │      │                     │
│                     │      │ planning            │      │                     │
└─────────────────────┘      └─────────────────────┘      └─────────────────────┘
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Investigate (site specific) external factors → Gather information and develop rough idea of size, shape etc. in order to use sensible values for the parameters in mine design and planning → Mine Design, including all its sub-stages

Create these multiple designs with the mine design software ← During Mine Panning, at the step of bench and haul road design, use FPC to investigate different fleets and thus haul road layouts ← Mine Planning, including all its sub-stages

Compare the desired, project specific KPI's, i.e. maximize NPV, IRR or ore extraction → Decide on optimal fleet selection and proceed with the further design steps, implementing the required haul road width and grade → Complete the rest of the design steps to achieve the final pit layout

FIGURE 26. FLOWCHART THAT ILLUSTRATES THE DIFFERENT STEPS TO COME TO AN OPTIMAL SOLUTION

6   DISCUSSION

In this chapter, the obtained results from both the literature review and the case study will be discussed and statements on their usefulness are made related to the original hypothesis. Besides this, other scenarios than those that have been investigated in the case study will be considered, and their expected outcomes based on the obtained results will be discussed. Additionally, a discussion on the use of autonomy versus manual fleets will be stated, using the results that are obtained throughout this thesis for guidance.

As can be seen in the previous chapter, the results of the literature review and case study have been used to answer the research questions. Based on these results a flowchart was constructed on how to run through the design process while implementing fleet selection via FPC. It is important to note that this flowchart, and the conclusions drawn, are only based on the results obtained from the literature review and the case study concerning the three different pits. The models have been created in collaboration with a mine design consultant and the results obtained are valued trustworthy. However, it is always important to critically assess the results and consider if similar outcomes can be obtained with other experiments.

A very important aspect of the flowchart and the steps that were undertaken in the case study is the fact that the entire process depends on site-specific variables. Conditions that govern the mine design and planning process are different for each project location and therefore it is not possible to come to a unique approach that can be simply adopted everywhere. The results that were obtained in this case study were based on three simplified, relatively small pits, not taking into account many of the factors that also will have an impact on the design process. Therefore it cannot be said that the obtained results can be expected for each project.

6.1   ALTERNATIVE SCENARIOS

In the case study, certain scenarios regarding alternative haul road characteristics were investigated, where others will be discussed here. There is a large range of different scenarios that can be investigated, but because of a limited amount of time and data, the results obtained in the case study will be extrapolated to analyze other scenarios.

Three pits were designed in the case study, with various sizes and grades, based on the literature and the available data. This way three realistic gold deposit cases were created and used for the analysis of different haul road characteristics. However, it is also interesting to discuss what the expected results would be under different circumstances, for example, an equal grade for all three deposits. These scenarios will be explained below.

6.1.1   ALTERNATIVE GOLD GRADE

The gold grade that is used in the geological model has an influence on the economic model, which eventually impacts the ultimate pit limits. With a lower gold grade, the ultimate pit will thus be smaller, and with a higher grade, the limits will be larger. Therefore a change in gold grade will simply impact the size of the ultimate pit on which the various haul road characteristics can be tested. The expected results for a different gold grade can, therefore, be linked to the results obtained from the three different (ultimate) pit size comparisons.

6.1.2   ALTERNATIVE DEPOSIT SIZE

Changing the deposit size while keeping the same grade basically has the same impact as maintaining the same deposit size but changing the gold grade. A larger deposit size will result in a larger ultimate pit but is dependent on the grade distribution throughout the deposit. Therefore an increase in deposit size does not result in a one-to-one increase in ultimate pit limits. A larger deposit also provides the possibility for lower production costs since larger equipment can be used, which will influence the ultimate pit additionally.

In general, assuming that an increase in the deposit size will result in an increase in the ultimate pit limit and vice versa, the conclusion can be drawn that the results that are obtained from comparing the three different pit sizes can be extrapolated to this scenario.

6.1.3 SWITCHBACKS

In the current designs, no switchbacks are implemented. This is done for a number of reasons. First, according to Hawlitschek (2018), the implementation of switchbacks in a mine design should be limited as much as possible, taking all decisive factors into consideration. The reason behind this is that switchbacks, due to their required extra width, have an extensive influence on the mine design's geometries, which is described by Tannant and Regensburg (2001) in the literature review. Besides this, the cases that were investigated were focused on different haul road widths and grades, adding a switchback only adds another variable that might influence the desired results.

As mentioned, the addition of a switchback is not preferable regarding the mine design, resulting in an increase in stripping ratio and extra construction costs. Also, a switchback will influence the travel time of the haulage equipment, since on a switchback speed limits are applicable as described by Poniewierski (2018). A switchback also influences the durability of the equipment due to extra stresses resulting from the sharp corners which is discussed by Kaufman and Ault (1977). This on its turn affects the productivity of the haulage equipment and is therefore not desirable. Note that the addition of a switchback is a very site-specific consideration, and the statements made above are applicable to normal or average conditions.

6.1.4 ALTERNATIVE HAUL ROAD GRADE

In the case study, three different haul road grades have been investigated, all based on the medium sized pit. Increasing the grade of a haul road results in a decrease of stripping ratio and haul road length, and thus improving the theoretical NPV of a project, where lowering the haul road grade will work the opposite way. The downside of increasing the grade of a haul road is the effect on the haul truck's performance and thus the productivity, which is described by Tannant and Regensburg (2001) and Masabattula (2011) in the literature review. There will be an increase in wear on the machine and the cycle times will be increased.

The possibility and the impact of increasing the haul road grade is very much site-specific and must, therefore, be thoroughly investigated for each project. If parameters such as geotechnical properties, climatic conditions, and haul road maintenance allow for the increase of the haul road grade, this is something worth investigating. Especially concerning larger and deeper deposits, the increase of haul road grade will likely result in a net increase in projects value because the positive impact on the stripping ratio is greater than the negative impact on the truck's performance. It is clear that there is

a boundary to which haul road grade is most profitable for a project, however, this exact boundary is not investigated in this study since it is again very much dependent on site-specific variables.

6.1.5 ALTERNATIVE HAUL ROAD WIDTH

As can be seen from the results obtained in the case study, increasing the haul road width will result in a higher stripping ratio but also lower haulage costs due to larger equipment. There is a fine line that will dictate what the optimum haul road width is, in combination with the larger equipment. For example, the higher investment of larger equipment will also have to be taken into account, complying with the site-specific life of mine. On the other hand, in the literature review, multiple sources have identified other concerns related to larger equipment sizes, and therefore these aspects should be taken into account as well.

When comparing the different sizes of the pits, it can be said that with increasing geometries the difference in percentage related to the impact on the design will decrease. This can be explained by the fact that with increasing deposit geometries, the haul road width does not have to increase proportionally as well. However, for larger deposits with more production there is more room for viable possibilities and thus comparison. This way, for example, five different haul road widths can be compared. This gives the operator more options in order to determine an optimal solution.

6.2 Autonomy

Implementing autonomous haulage trucks has proven to lower the haulage costs by increasing the productivity and also decreasing the downtime in certain open pit operations in the Pilbara Region in Australia as described by Redwood (2018). Besides this, Meech and Parreira (2011) stated that an autonomous fleet is safer, since no personnel is required to drive the trucks, eliminating the risk of loss-time-injuries. However, there are also some conditions that apply before the implementation of an autonomous fleet in a mine design can be justified, as was described by Nebot (2007) in the literature review. These conditions vary from deposit type and geometry to the political stability of the country in which the project is situated, and will be explained below.

6.2.1 Deposit Type, Size and Geometry

The type of ore and the geometry of the deposit have a significant impact on the decision for autonomy. Any autonomous machine works best under predictable and constant conditions, as was described by Nebot (2007) in the literature review. This means that regarding the deposit type, a homogenous distribution of ore is desirable, resulting in a low required mining selectivity. A homogenous ore distribution also impacts the mine designs contours, allowing for the possibility to create a design that suits autonomy by excluding complicated road intersections for example. However, a homogenous ore distribution is something that doesn't occur regularly in reality and is dependent on, for example, how the deposit is formed. This illustrates that the deposit type already puts restrictions on which types of ore are suitable for autonomy, and puts limits on the design options, as was stated in the literature review.

Besides this, the size of the deposit can dictate if autonomy is a realistic option. Implementing an autonomous fleet will require a higher level of capital investment compared to a manned fleet. If the deposit is not of an adequate size, the life of mine will be shorter and therefore it is possible that the investment requirements for an autonomous fleet cannot be justified.

6.2.2 Possibility for Increased Investments

As described above, the capital investment for an autonomous fleet is larger compared to a manned fleet. To justify the choice of making such an extra investment there has to be a relatively high level of certainty on certain variables, as described by Park and Matunhire (2011). For example, there must be

decisive evidence that the life of mine is extensive and that extraction is still profitable under decreasing economic conditions. If these factors cannot be guaranteed, a mining company might be less willing to make a larger investment than necessary. What can be an option in these cases is retrofitting, where an existing, manned fleet, is transformed into an autonomous fleet. This can be done after the mine has run for a couple of years and certainty levels have risen due to an increased availability of data.

6.2.3 POLITICAL STABILITY

Again, regarding the high required investment, not every country might be suitable for the implementation of an autonomous fleet. There are numerous countries which are politically highly unstable, causing mining companies to decide for a safer approach regarding investments made in those areas. Any company will assess the risks associated with the investment, which will be higher in these countries. This might make the difference concerning the decision for autonomous or manned haulage trucks.

On the other hand, the argument can be given that due to autonomy there is less workforce on site, and thus less risk regarding the personnel. The autonomous trucks can be operated from a command center thousands of kilometers away, in a safe and stable environment. Both these considerations will be taken into account by mining companies, and depending on the structure and vision of the company decisions will be made on the most suitable strategy.

6.2.4 OPERATING COSTS

The demand for autonomy is on one side based on safety, but mainly on saving costs. The idea is that the extra expenses made on capital investment can be overcome by a decrease in operating costs, which is demonstrated by Redwood (2018). An autonomous fleet does not require truck operators, and especially regarding large operations, this could mean a significant saving in operational costs. However, one thing that has to be taken into account regarding this is that operating costs, and especially truck driver salaries, are not equal for every country, which can make a difference on this equation. Also accommodating and transporting the required personnel can be seen as a significant cost post. When deciding if autonomy is beneficial compared to manned, it is thus important to consider the (local) salaries, and the costs for relocation and accommodation as well, in order to come to a sound conclusion.

Besides this, the implementation of autonomy will eliminate the need for truck drivers on one hand, but on the other, highly trained operators will be needed in the command center. These people require a higher degree of education and will, therefore, be more expensive, meaning that the costs saved on personnel might not be as large as anticipated. This illustrates that thorough research regarding the benefits and downsides related to autonomy should be executed before any decisions are made.

6.2.5 HIGH R&D COSTS

The research and development (R&D) costs related to autonomous trucks are high, since it embraces a new, state of the art development. This investment, made for R&D related to autonomy, will need to be earned back. This will mean that those expenses will be translated to the cost price of an autonomous vehicle. If these costs can be distributed over a large number of sold vehicles, illustrating a high demand for autonomous trucks, the increase in cost will be relatively low. If, however, the demand is low, the same R&D costs have to be distributed over a lower number of vehicles, increasing the catalog price of these trucks.

6.2.6 COMBINATION OF FACTORS

Combining these factors it is understandable that the implementation of autonomous trucks in for example Australia can be seen as a success. Here, the trucks are used in relatively homogenous, very large iron ore deposits, with a life of mine that runs over tens of years. Also, the political environment in Australia is stable and the wages of truck drivers are amongst the highest in the world. These factors justify the implementation of autonomy in these cases. When considering the implementation of autonomy in other deposits over the world it is therefore very important to look at these different factors and conduct a thorough research on the advantages and disadvantages.

6.3   AUTONOMY RELATED TO THE CASE STUDY

Relating the statements made above with the cases investigated in the case study, it is possible to draw some conclusions. Regarding the size and shape of the deposits, including the life of mine, these deposits will not be considered suitable for an autonomous fleet. This is simply because the life of mine is not sufficient to justify the investments necessary for autonomous equipment. However, the results that were obtained regarding the haul road characteristics can be used to assess the advantages of an autonomous fleet under comparable conditions.

Based on the obtained results, it is clear that smaller haul roads will improve the economic scenario of any operation, where the highest potential lays with the larger deposits. When using an autonomous fleet, the safety margins that are now used to determine the width of a haul road in relation to the width of a truck might be decreased ever so slightly. This can be achieved since there is no human operator anymore, which is also described by Redwood (2018). This will then result in smaller roads for the same trucks, while keeping the same production, and thus improving the economic scenario of a project.

One downside with smaller haul road widths is that the equipment size gets smaller as well, and thus increases the Opex, especially when concerning, for example, the number of truck operators and their salaries and the fuel consumption. If for these trucks autonomy would be used, one of the cost posts, operators, could be eliminated, counteracting the negative aspects of a smaller equipment size. On the other hand, an increase in the number of vehicles will result in an increase in fuel costs, and this is something to take into account as well.

Using smaller equipment would also have other benefits, for example, an increase in operational selectivity and flexibility, and a decrease on the risk of underproduction due to downtime of one truck. This counteracts the concerns described by Gilewicz (2002) and Krause (2001) related to the ever-increasing equipment size. On the other hand, smaller equipment would mean an increase in the number of trucks to meet the same production rate, and the length of the haul road must be sufficient to accommodate these trucks in order to avoid bunching.

These examples show that the implementation of autonomy on (smaller) trucks has positive impacts on the required haul road widths, and also creates other advantages as well. Therefore this might be something worth for future investigation.

7   CONCLUSIONS

In the thesis, several research questions have been answered in order to make conclusions regarding the main hypothesis. It is clear that there is a possibility to implement fleet selection trough FPC within the mine design process, preferably following the flowchart that was stated in the evaluation. The conclusions listed below are divided into three parts: general conclusions on the processes and the parameters that govern them, the influence alternative haul road designs have on the mine design and the equipment, and the possibility of autonomy related to this investigation.

7.1   GENERAL

One of the outcomes of the study is that it has clearly illustrated that the processes of mine design, planning, and equipment selection are circular processes, and where decisions made at one stage will limit the options in later stages. Besides this, these processes are dependent on countless different variables, of which many turn out to be heavily dependent on the specific site or location. This implies that, in order to come to the best possible match between equipment selection and mine design, these variables have to be assessed for each site specifically, and therefore a general approach would not be suitable.

7.2   HAUL ROAD INFLUENCE

In the case study, it has been proven that changes in haul road design have a significant impact on the mine geometries and therefore the economic situation of a project. Increasing the width or decreasing the grade of a haul road has resulted in increasing mine geometries and thus an increase in stripping ratio and extra waste removal, resulting in a negative economic scenario. Decreasing the width or increasing the grade has the opposite effect, and besides this, the percentual difference between scenarios decreases as deposit geometries increase.

Changes regarding haul road width and grade also have an impact on equipment selection and performance. A smaller width resulted in a smaller equipment size with a generally higher Opex compared to larger equipment. An increase in haul road grade resulted in a decrease in the truck's performance and thus an increase in maintenance costs and a reduced lifetime, where the effect on small trucks is more significant compared to large trucks.

Alternative haul road designs also impact the costs associated with construction and maintenance of those haul roads. With increasing widths and decreasing grades, the constructions costs will generally increase, where the maintenance costs will increase, specifically with increasing haul road grades.

7.3   AUTONOMY

Autonomy is a development that can offer interesting possibilities in combination with the results that are obtained from the study. However, the implementation of autonomy is dependent on a lot of complex, site or country-specific variables. Therefore a thorough analysis regarding the implementation of autonomy should be made for each site in specific. If the implementation of AHS is possible, and for example, fitted on smaller haul trucks, the choice for autonomy could result in multiple benefits. These range from narrower haul road widths with the same production rates, and thus a lower stripping ratio, to a decrease of Opex, and an increase in safety, production flexibility, and selectivity. These conclusions show that there is still room for economic improvement regarding the interaction between equipment selection and mine design, particularly in combination with the integration of autonomy.

8   RECOMMENDATIONS

The first point to discuss is the software that is used for this study and the data required for this. To obtain the results from the case study, several different, very specific software packages had to be used, ranging from mine planning software to Caterpillar's FPC. In order to come to the best possible results, profound knowledge of, and easy access to these packages is crucial. If the goal is to investigate the hypothesis of this thesis further, the advice is to deepen the knowledge regarding especially mine planning software or construct a collaboration with a company that can offer this knowledge.

Besides this, the quality of a case study is dependent on the quality of the data that is used. If there is no available data to work with, this has, as can be seen in the case study, negative consequences on the quality of the work. Therefore it is strongly recommended that in future projects relevant and useful data is provided to ensure the quality of the results and that they deliver to the expectations.

The next point is the situation that is investigated. In the thesis, the emphasis was laid on a Greenfield project, since the goal is to determine the best economic scenario before operations start. However, to test the hypothesis it might be worthwhile to first investigate this on proven deposits that are already operating for a number of years.

The advantage of this approach is that these deposits already have a mine design and plan in place and a proven production over multiple years. This will save a lot of work, and the economic situation regarding, for example, the costs per ton is very reliable. Besides this, the impact of external factors can be investigated in such a case, especially if multiple mines in different environments are compared to each other for example. If then the hypothesis is proven under more realistic conditions with multiple external factors in play, the concept can possibly be implemented on Greenfield projects.

Besides this, since it is proven that decreasing the haul road width has a positive influence on a projects economic scenario, and the fact that this haul road width is governed by the haul truck width, it might be interesting to investigate the ratio of payload to truck width. If the payload of a truck could be increased by keeping the truck width equal, the results regarding the economic situation could be significant. However, this is something that embraces a different field of study and should, therefore, be investigated separately.

In general, the results of the case study show interesting possibilities for the implementation of AHS. For example, decreasing safety margins would lead to a significant reduction in haul road width, and

thus a more positive economic scenario. However, there are strict rules that dictate these safety margins, and therefore an extensive study on this aspect should be carried out.

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FIGURE 27. CUMULATIVE FREQUENCY PLOT OF ORE TONNAGES FOR SEDIMENT HOSTED DEPOSITS. BERGER, MOSIER, BLISS, AND MORING, 2014.
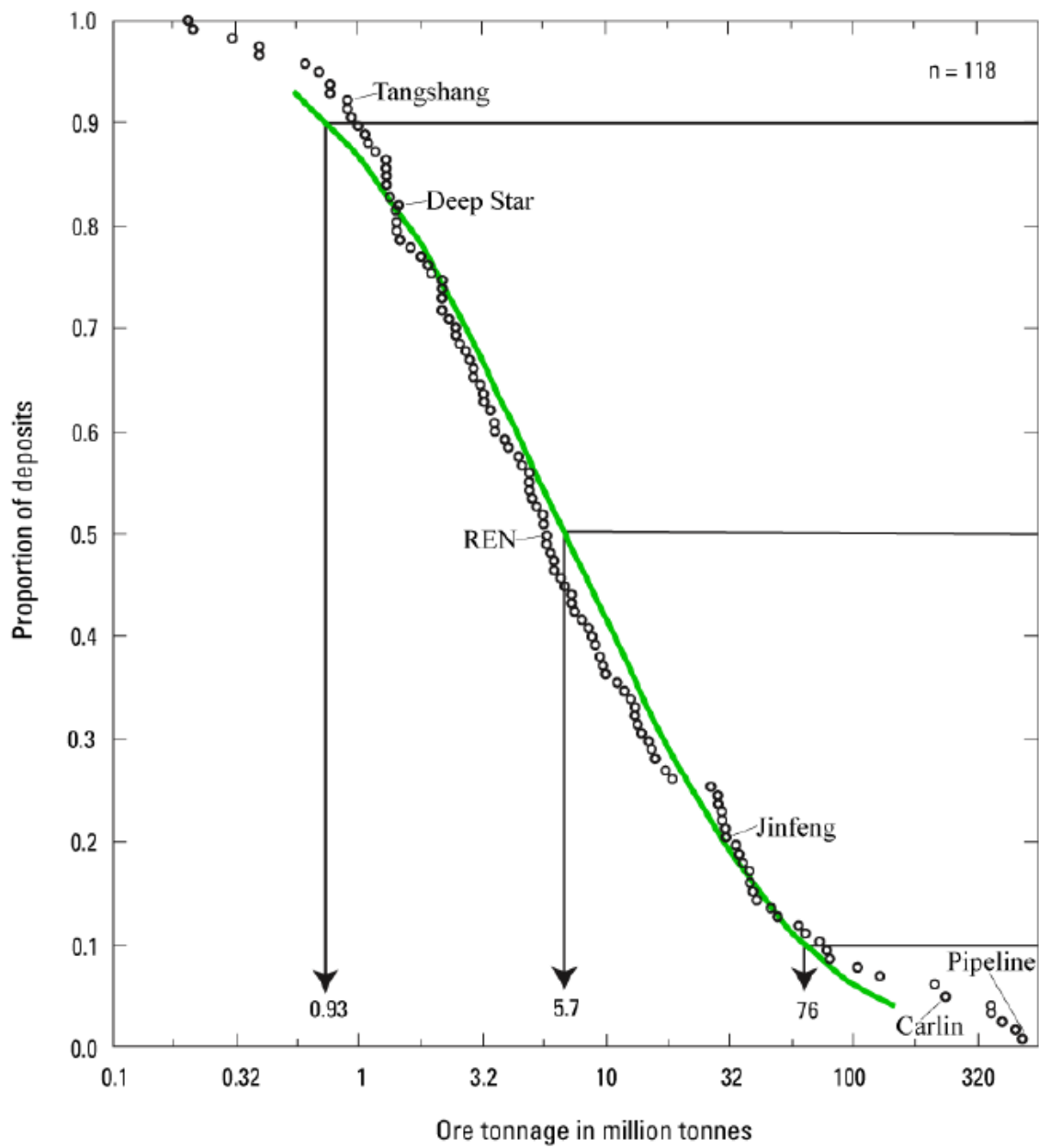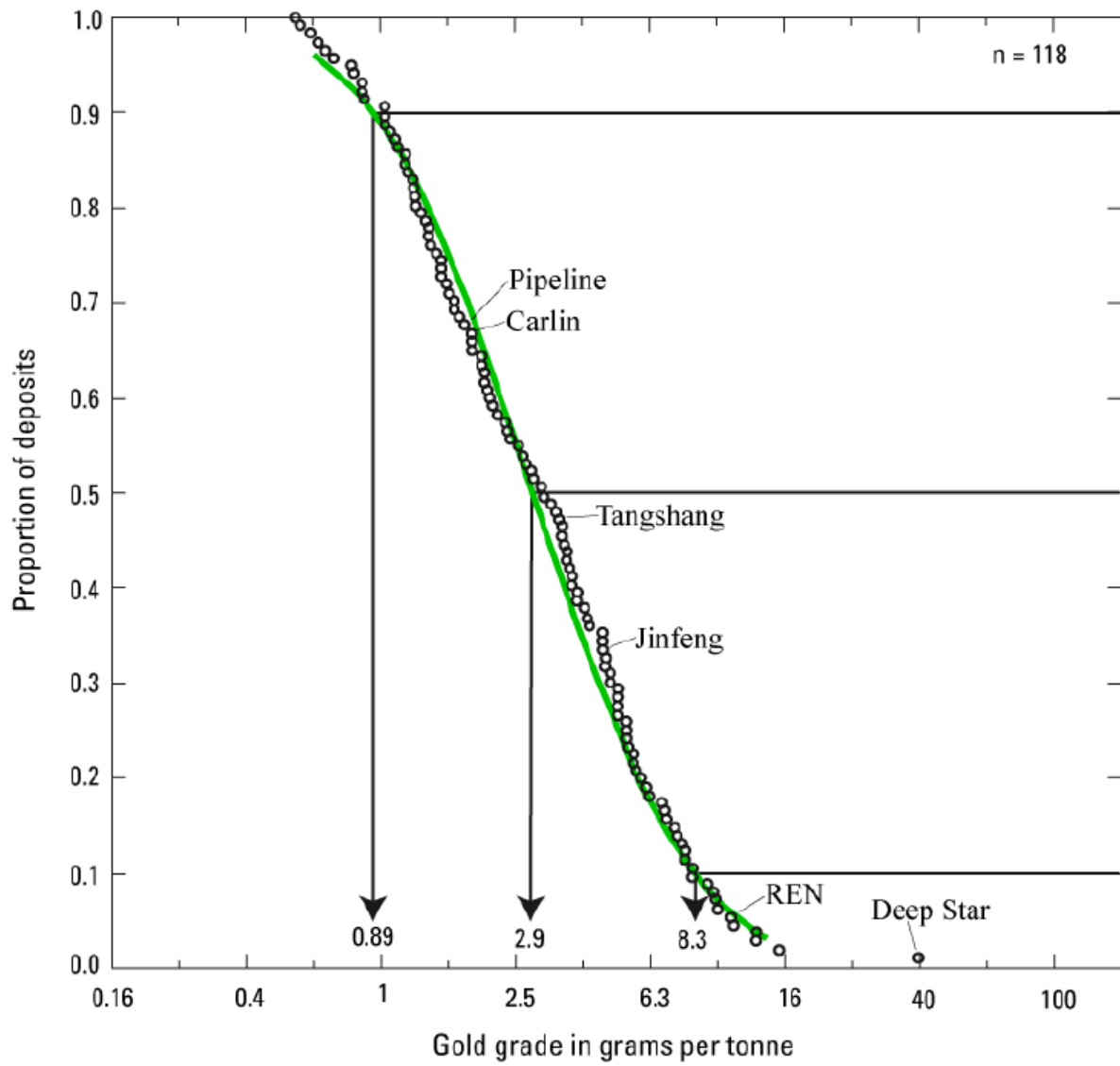
FIGURE 28. CUMULATIVE FREQUENCY PLOT OF GOLD GRADES FOR SEDIMENT HOSTED DEPOSITS. BERGER, MOSIER, BLISS, AND MORING, 2014.
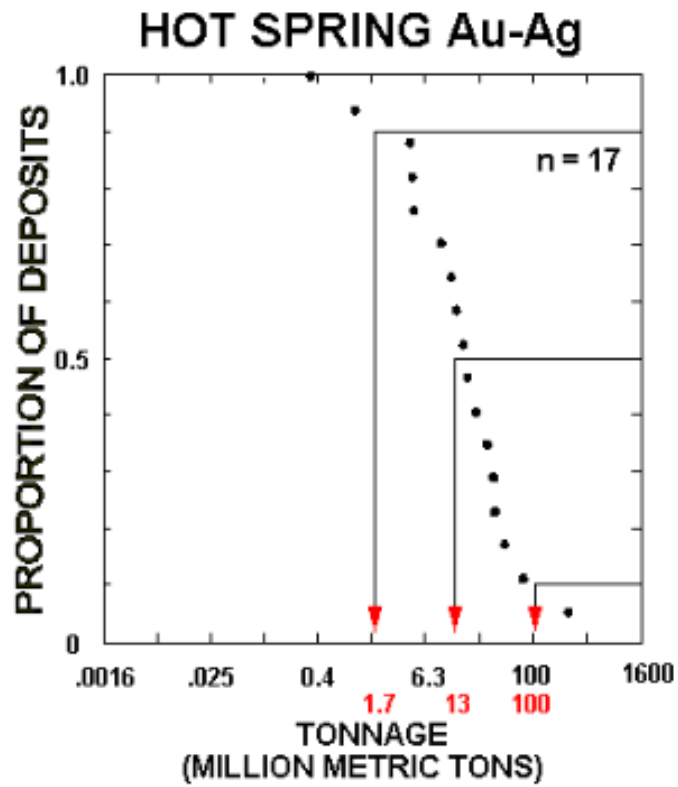
FIGURE 29. CUMULATIVE FREQUENCY PLOT OF TONNAGES FOR HOT SPRING GOLD DEPOSITS. BERGER AND SINGER, 1987.
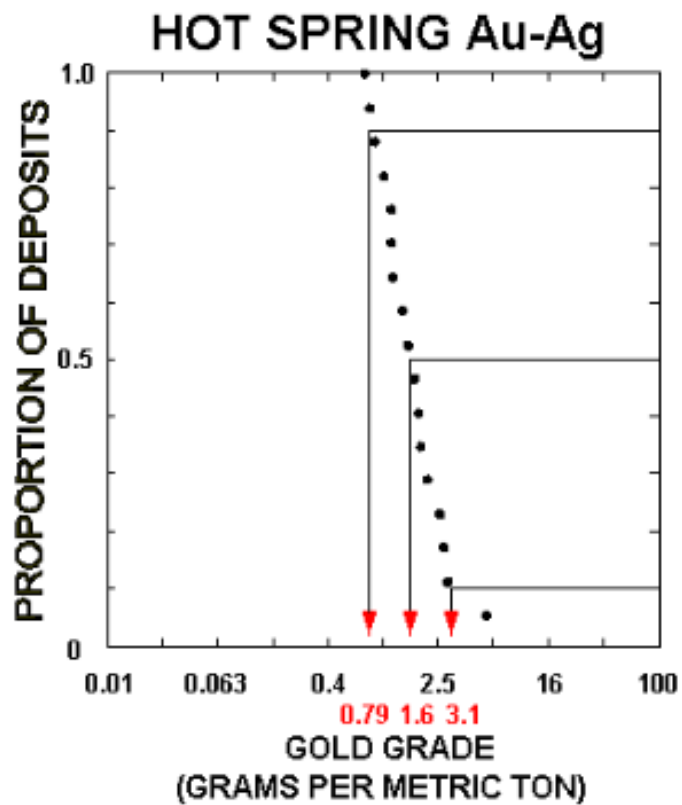

FIGURE 30. CUMULATIVE FREQUENCY PLOT OF GOLD GRADES FOR HOT SPRING DEPOSITS. BERGER AND SINGER, 1987.

APPENDIX B – NPVSCHEDULER PARAMETERS AND RESULTS

TABLE 21. ECONOMIC MODEL STATISTICS OF THE SMALL AND LARGE PIT

Statistics	Small pit	Large pit
Revenue (US $)	6 002 275 405	1 240 447 594
Processing Costs (US $)	449 209 594	396 344 418
Mining Costs (US $)	5 196 176 859	5 196 175 859
Net Value (US $)	356 199 472	(4 352 073 684)
Ore Value (US $)	5 383 557 656	676 665 908

TABLE 22. PARAMETERS USED FOR ULTIMATE PIT CALCULATIONS OF THE SMALL AND LARGE PIT

Parameters	Small pit	Large pit
Annual discounting	8%	8%
Average output rate per 365 days	77 000 tons	1 300 000 tons
Incremental factor	5%	5%
Slope of region 1 (WROCK)	60 degrees	60 degrees
Slope of region 2 (SOIL)	30 degrees	30 degrees
Slope of region 3 (SROCK)	45 degrees	45 degrees
Slope of region 4 (ORE)	60 degrees	60 degrees

TABLE 23. ULTIMATE PIT STATISTICS OF THE SMALL PIT, EXTRACTED FROM NPVSCHEDULER

Global Stats							
Cash	Revenue	Process Cost	Mining Cost	Net Value	NPV	V3 NPV	Ore Value
	5,978,048,012	447,506,794	424,052,229	5,106,488,989	500,933,579	847,585,901	5,365,012,016
	Block Count	Mass					
ORE	1,418	23,790,898					
Waste	5,615	59,037,676					
Total	7,033	82,828,574					
Strip Ratio	2,48152365987						
ORE Stats							
	Mass	AUgrade	AUgrade Min	AUgrade Max	AUgrade R	AUgrade R Min	AUgrade R Max
	tonnes	g	g/tonne	g/tonne	g	g/tonne	g/tonne
ORE	23,790,898	178,769,378	1,2625	38,5280	149,451,202	1,2625	38,5280

TABLE 24. ULTIMATE PIT STATISTICS OF THE LARGE PIT, EXTACTED FROM NPVSCHEDULER

Global Stats							
Cash	Revenue	Process Cost	Mining Cost	Net Value	NPV	V3 NPV	Ore Value
	1,017,942,878	284,892,347	184,163,518	548,887,013	434,084,879	450,976,906	624,136,894
	Block Count	Mass					
ORE	868	15,145,791					
Waste	1,803	20,640,526					
Total	2,671	35,786,317					
Strip Ratio	1,36278953321						
ORE Stats							
	Mass	AUgrade	AUgrade Min	AUgrade Max	AUgrade R	AUgrade R Min	AUgrade R Max
	tonnes	g	g/tonne	g/tonne	g	g/tonne	g/tonne
ORE	15,145,791	30,440,875	0,6403	8,2191	25,448,572	0,6403	8,2191

TABLE 25. PARAMETERS USED TO CREATE THE SCHEDULES OF THE SMALL AND LARGE PIT

Parameters	Small pit	Large pit
Consumption rate total Rock	438 000 tons	2 299 500 tons
Primary objective	Maximize NPV	Maximize NPV

TABLE 26. SCHEDULE RESULTS OF THE SMALL PIT. HIGHLIGHTING IN GREEN WHICH YEAR OF THE SCHEDULE WILL BE USED FOR EXPORT, EXTRACTED FROM NPVSCHEDULER

Year	Rock tonnes	Revenue $	Processing Cost $	Mining Cost $	NPV $	ORE tonnes	ORE (w) tonnes	WROCK tonnes	SOIL tonnes	SROCK tonnes	AUgrade g	AUgrade R g	Strip	Cumulative Total Tonnage	Cumulative ORE	Cumulative NPV
1	4,52E+05	1,87E+08	5,93E+06	2,26E+06	1,7E+08	3,15E+05	0	0,00E+00	1,36E+05	0,00E+00	5,60E+06	4,68E+06	0,431627	4,52E+05	3,15E+05	$ 170.102.032,00
2	4,48E+05	1,40E+08	4,39E+06	2,16E+06	1,16E+08	2,33E+05	0	3,48E+04	1,80E+05	0,00E+00	4,18E+06	3,50E+06	0,919633	8,99E+05	5,49E+05	$ 285.973.219,00
3	4,30E+05	1,73E+08	5,79E+06	2,16E+06	1,33E+08	3,08E+05	0	0,00E+00	1,22E+05	0,00E+00	5,18E+06	4,33E+06	0,397661	1,33E+06	8,57E+05	$ 419.224.079,00
4	4,42E+05	2,15E+08	6,40E+06	2,27E+06	1,54E+08	3,40E+05	0	1,60E+03	9,96E+04	5,50E+02	6,44E+06	5,38E+06	0,29898	1,77E+06	1,20E+06	$ 573.632.106,00
5	4,31E+05	2,02E+08	6,60E+06	2,31E+06	1,34E+08	3,51E+05	0	5,27E+04	2,78E+04	0,00E+00	6,05E+06	5,06E+06	0,229447	2,20E+06	1,55E+06	$ 707.164.704,00
6	2,14E+05	1,32E+08	3,52E+06	1,17E+06	83032190	1,87E+05	0	2,69E+04	0,00E+00	2,75E+02	3,94E+06	3,30E+06	0,145175	2,42E+06	1,74E+06	$ 790.196.894,00

TABLE 27. SCHEDULE RESULTS OF THE MEDIUM PIT. HIGHLIGHTING IN GREEN WHICH YEAR OF THE SCHEDULE WILL BE USED FOR EXPORT, EXTRACTED FROM NPVSCHEDULER

Year	Rock tonnes	Revenue $	Processing Cost $	Mining Cost $	NPV $	ORE tonnes	ORE (w) tonnes	WROCK tonnes	SOIL tonnes	SROCK tonnes	AUgrade g	AUgrade R g	Strip	Cumulative Total Tonnage	Cumulative ORE	Cumulative NPV
1	1,44E+06	1,45E+08	1,78E+07	7,13E+06	1,1E+08	9,44E+05	0,00E+00	3,04E+03	4,93E+05	4,33E+03	4,32E+06	3,61E+06	0,53	1,44E+06	9,44E+05	$ 114.845.231,00
2	1,44E+06	2,24E+08	2,35E+07	7,65E+06	1,7E+08	1,25E+06	3,74E+03	3,30E+04	1,49E+05	3,37E+03	6,71E+06	5,61E+06	0,151	2,88E+06	2,19E+06	$ 285.341.817,00
3	1,40E+06	1,49E+08	1,47E+07	6,84E+06	1E+08	7,84E+05	5,70E+03	1,09E+05	4,90E+05	6,94E+03	4,44E+06	3,71E+06	0,781	4,28E+06	2,98E+06	$ 387.927.783,00
4	1,42E+06	1,08E+08	1,57E+07	6,96E+06	6,5E+07	8,35E+05	0,00E+00	3,27E+04	5,12E+05	4,07E+04	3,22E+06	2,69E+06	0,7	5,70E+06	3,81E+06	$ 452.915.637,00
5	1,42E+06	2,71E+05	2,01E+04	5,47E+06	-4E+06	1,07E+03	0,00E+00	3,38E+03	1,42E+06	0,00E+00	8,10E+03	6,77E+03	1328	7,12E+06	3,81E+06	$ 449.267.476,00
6	1,43E+06	5,48E+06	5,53E+05	6,71E+06	-1E+06	2,94E+04	0,00E+00	8,44E+05	5,54E+05	0,00E+00	1,64E+05	1,37E+05	47,58	8,55E+06	3,84E+06	$ 448.112.985,00
7	1,43E+06	5,46E+07	5,54E+06	7,48E+06	2,4E+07	2,95E+05	1,78E+06	1,10E+06	3,53E+04	0,00E+00	1,63E+06	1,37E+06	9,889	9,97E+06	4,14E+06	$ 472.327.812,00
8	1,42E+06	1,22E+08	1,30E+07	7,62E+06	5,6E+07	6,90E+05	0,00E+00	7,32E+05	0,00E+00	0,00E+00	3,66E+06	3,06E+06	1,061	1,14E+07	4,83E+06	$ 527.949.188,00
9	1,42E+06	1,27E+08	1,71E+07	7,66E+06	5,1E+07	9,07E+05	0,00E+00	5,04E+05	0,00E+00	6,94E+03	3,80E+06	3,17E+06	0,564	1,28E+07	5,73E+06	$ 579.310.359,00
10	1,43E+06	1,33E+08	1,63E+07	7,72E+06	5,1E+07	8,64E+05	0,00E+00	5,62E+05	0,00E+00	6,33E+03	3,99E+06	3,33E+06	0,657	1,42E+07	6,60E+06	$ 630.009.731,00
11	1,18E+06	1,44E+08	1,63E+07	6,42E+06	5,3E+07	8,67E+05	0,00E+00	2,23E+05	0,00E+00	8,79E+04	4,32E+06	3,61E+06	0,359	1,54E+07	7,46E+06	$ 682.824.383,00
Total	15422568	1,212,387,	140,406,126	77,663,708	6,8E+08	7464440	9619	4142897	3649163	156449	36,255,619	30,309,699	1,066			

TABLE 28. SCHEDULE OF THE LARGE PIT. HIGHLIGHTING IN GREEN WHICH YEAR OF THE SCHEDULE WILL BE USED FOR EXPORT, EXTRACTED FROM NPVSCHEDULER

Year	Rock	Revenue	Processing	Mining Co	NPV	ORE	ORE (w)	WROCK	SOIL	SROCK	AUgrade	AUgrade F	Strip	Cumulative	Cumulative	Cumulative NPV
	tonnes	$	$	$	$	tonnes	tonnes	tonnes	tonnes	tonnes	g	g		Total Tonnage	ORE	
1	2,32E+06	8,10E+07	1,92E+07	1,08E+07	4,91E+07	1,02E+06	9,04E+04	3,04E+03	1,17E+06	3,26E+04	2,42E+06	2,03E+06	1,270208	2,32E+06	1,02E+06	$ 49.133.495,00
2	2,28E+06	3,74E+07	1,45E+07	1,03E+07	1,14E+07	7,71E+05	1,02E+05	5,57E+03	1,35E+06	5,01E+04	1,12E+06	9,36E+05	1,960252	4,60E+06	1,79E+06	$ 60.498.619,00
3	2,30E+06	7,20E+07	1,55E+07	1,05E+07	3,81E+07	8,24E+05	1,18E+05	3,21E+03	1,33E+06	2,43E+04	2,15E+06	1,80E+06	1,794027	6,90E+06	2,62E+06	$ 98.630.459,00
4	2,30E+06	6,66E+07	1,43E+07	1,08E+07	3,20E+07	7,62E+05	9,51E+04	3,14E+05	1,09E+06	4,44E+04	1,99E+06	1,67E+06	2,019449	9,20E+06	3,38E+06	$ 130.610.426,00
5	2,33E+06	5,92E+07	1,45E+07	1,20E+07	2,27E+07	7,69E+05	1,59E+05	1,09E+06	2,76E+05	3,19E+04	1,77E+06	1,48E+06	2,024203	1,15E+07	4,15E+06	$ 153.346.398,00
6	2,28E+06	7,67E+07	1,48E+07	1,20E+07	3,18E+07	7,89E+05	6,06E+04	1,34E+06	7,85E+04	7,70E+03	2,29E+06	1,92E+06	1,889784	1,38E+07	4,94E+06	$ 185.102.228,00
7	2,29E+06	3,75E+07	1,44E+07	1,22E+07	6,49E+06	7,67E+05	1,90E+05	1,29E+06	1,09E+04	3,74E+04	1,12E+06	9,37E+05	1,989454	1,61E+07	5,70E+06	$ 191.587.891,00
8	2,30E+06	7,74E+07	1,77E+07	1,23E+07	2,60E+07	9,41E+05	1,74E+04	1,34E+06	0,00E+00	1,79E+03	2,31E+06	1,93E+06	1,440371	1,84E+07	6,64E+06	$ 217.564.042,00
9	2,31E+06	7,21E+07	2,01E+07	1,24E+07	1,99E+07	1,07E+06	1,69E+04	1,20E+06	0,00E+00	1,60E+04	2,16E+06	1,80E+06	1,154098	2,07E+07	7,71E+06	$ 237.506.837,00
10	2,30E+06	7,43E+07	2,10E+07	1,23E+07	1,91E+07	1,11E+06	1,14E+04	1,15E+06	0,00E+00	2,22E+04	2,22E+06	1,86E+06	1,063019	2,30E+07	8,83E+06	$ 256.635.975,00
11	2,30E+06	6,72E+07	2,01E+07	1,23E+07	1,49E+07	1,07E+06	4,37E+04	1,16E+06	0,00E+00	2,63E+04	2,01E+06	1,68E+06	1,151904	2,53E+07	9,90E+06	$ 271.504.664,00
12	2,29E+06	1,01E+08	2,66E+07	1,24E+07	2,45E+07	1,42E+06	8,66E+04	7,53E+05	0,00E+00	3,84E+04	3,01E+06	2,52E+06	0,620175	2,76E+07	1,13E+07	$ 295.986.179,00
13	2,30E+06	1,02E+08	2,96E+07	1,25E+07	2,18E+07	1,57E+06	8,67E+04	5,39E+05	0,00E+00	1,02E+05	3,04E+06	2,54E+06	0,463392	2,99E+07	1,29E+07	$ 317.813.440,00
14	7,32E+05	2,95E+07	1,13E+07	4,01E+06	4,98E+06	5,99E+05	3,28E+04	4,01E+04	0,00E+00	6,00E+04	8,83E+05	7,38E+05	0,221876	3,06E+07	1,35E+07	$ 322.794.100,00

Regarding size control, to create the pushbacks and the schedules, for the small pit the 1st LG pit shell was used, for the medium the 9th and for the large deposit the 16th. The schedule files that are used for export are highlighted in green.

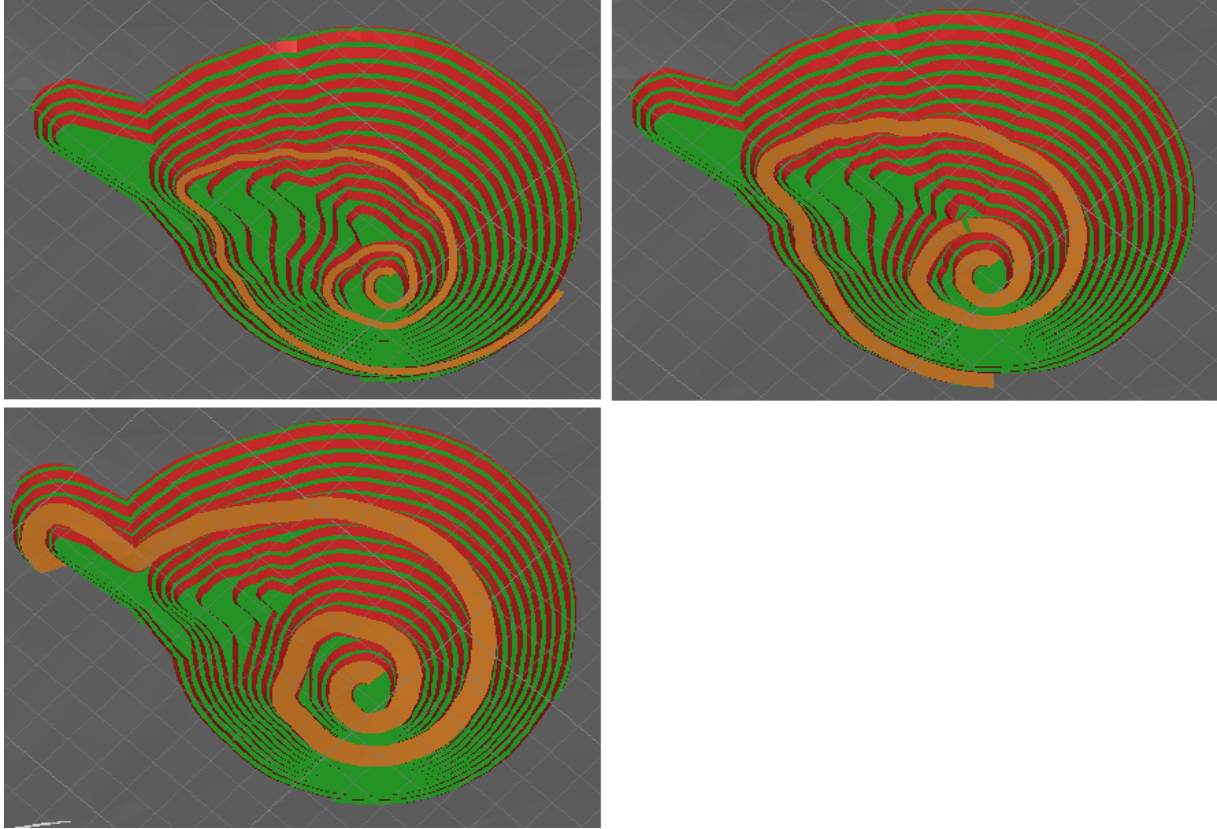# APPENDIX C – STUDIOOP PARAMETERS AND RESULTS

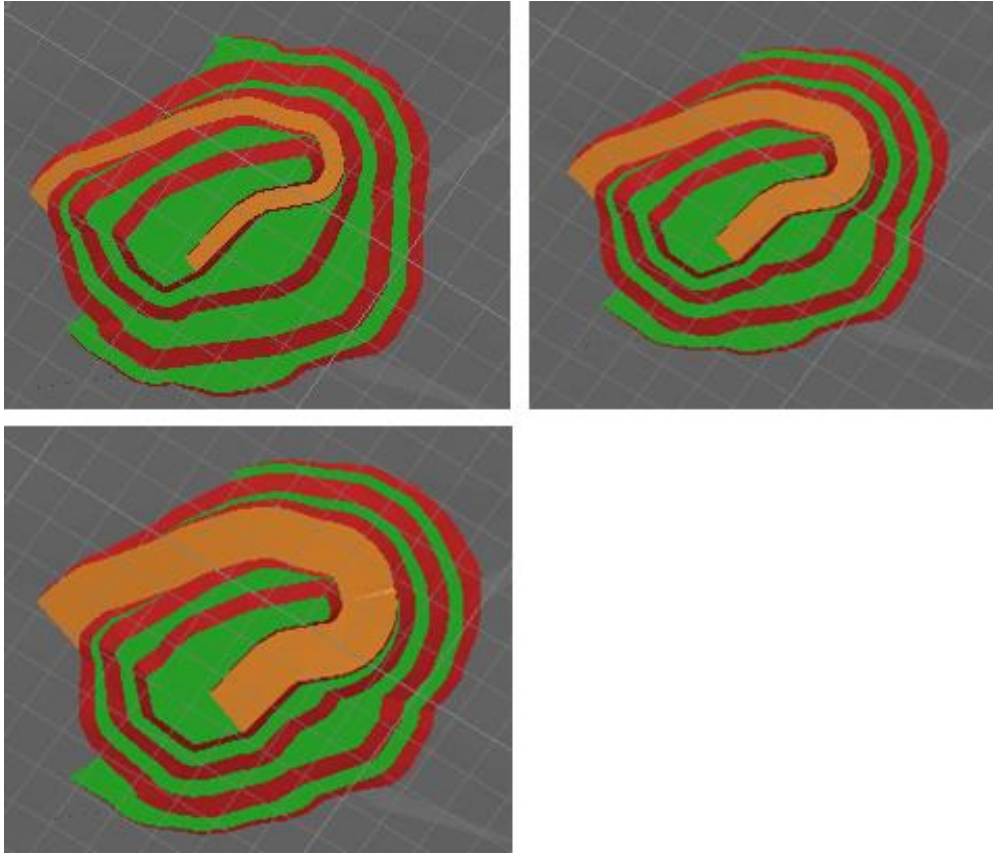**FIGURE 31. HAUL ROAD WIDTHS OF 10, 20 AND 30 METERS FOR THE LARGE PIT**

FIGURE 32. HAUL ROAD WIDTHS OF 10, 20 AND 30 METERS FOR THE SMALL PIT

Regarding the large pit design, it can be observed that changing the haul road width not only affects the design of the pit, but also changes the end point of the haul road. Due to the haul road generation program this is something which is very difficult to control, where the choice has to be made between keeping the starting point constant, or the end point. Here the choice was made to maintain a constant starting point.
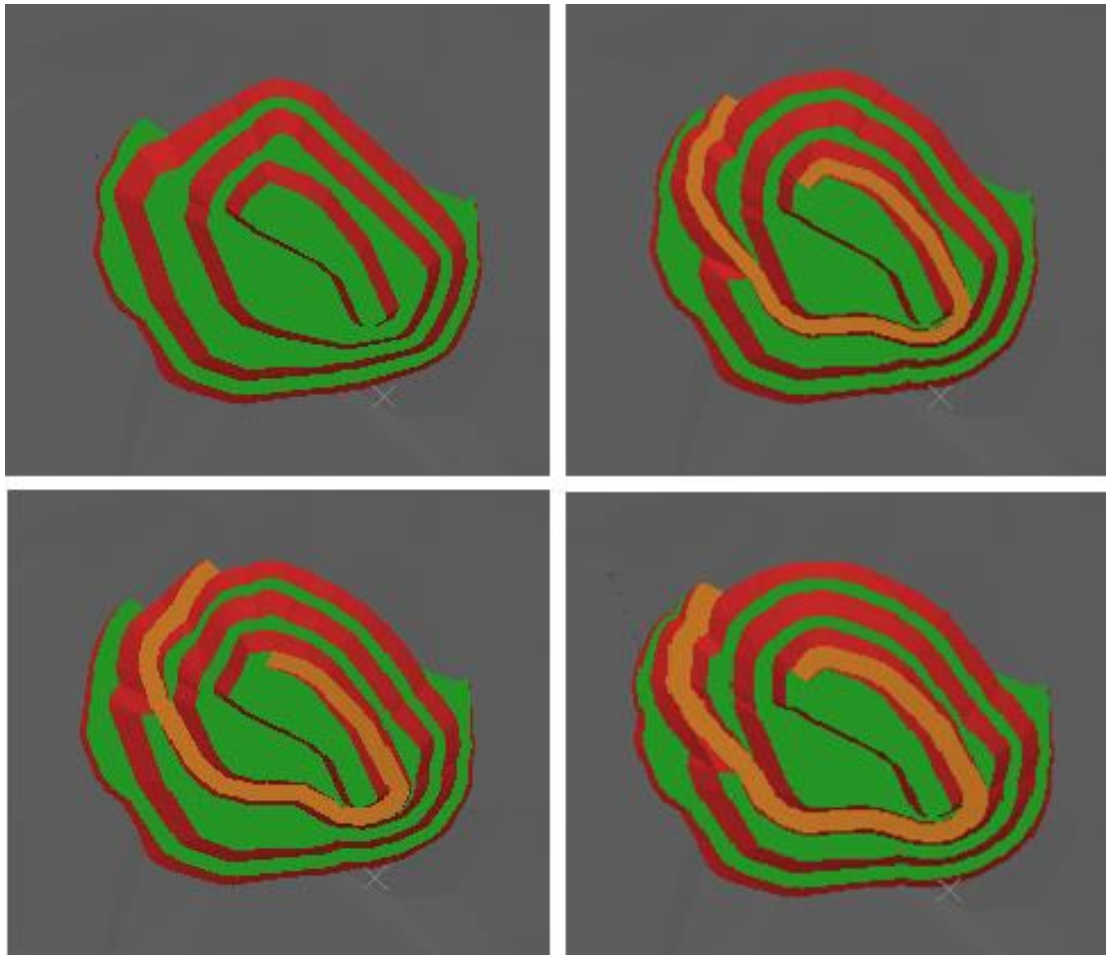
FIGURE 33. DESIGN OF THE MEDIUM PIT WITH THE CORRECT HAUL ROAD WIDTHS. TOP LEFT NO, TOP RIGHT SMALL, BOTTOM LEFT MEDIUM AND BOTTOM RIGHT LARGE ROAD
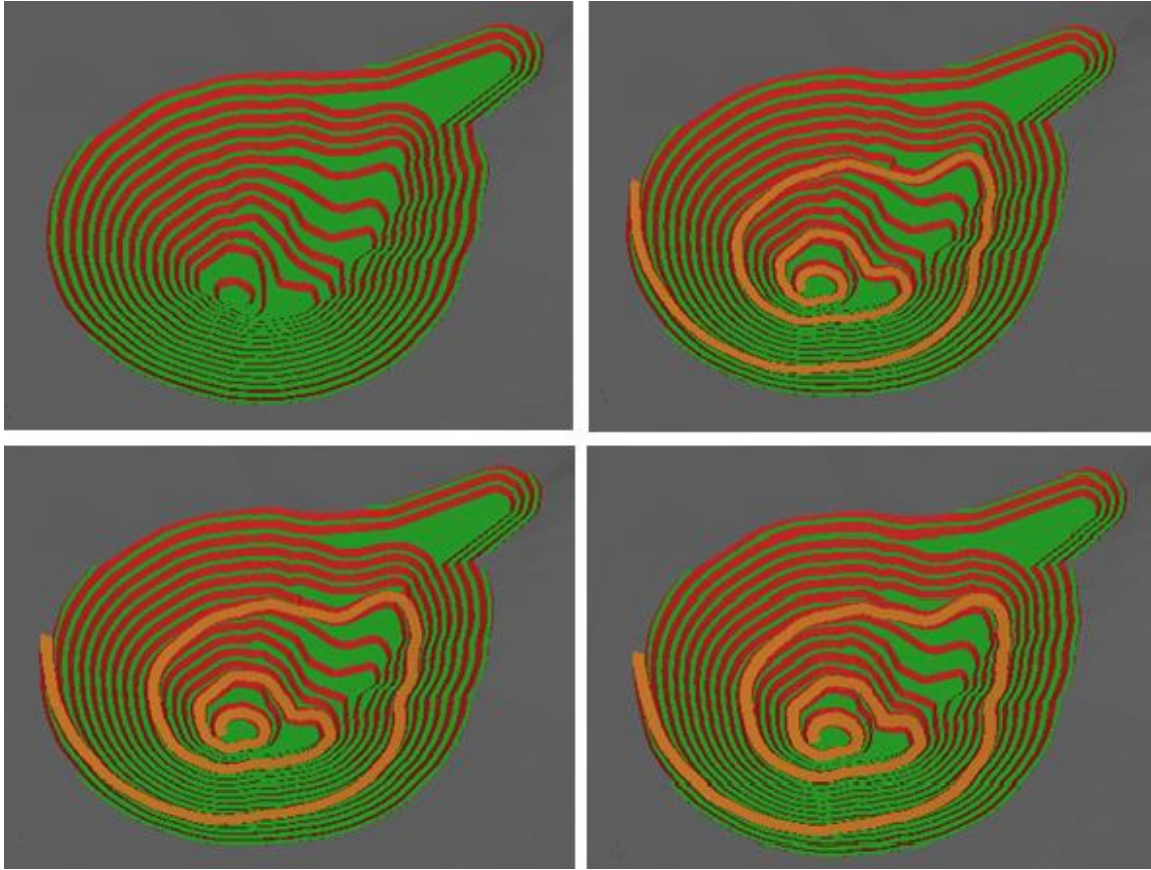
FIGURE 34. DESIGN OF THE LARGE PIT WITH THE CORRECT HAUL ROAD WIDTHS. TOP LEFT NO, TOP RIGHT SMALL, BOTTOM LEFT MEDIUM, AND BOTTOM RIGHT LARGE ROAD
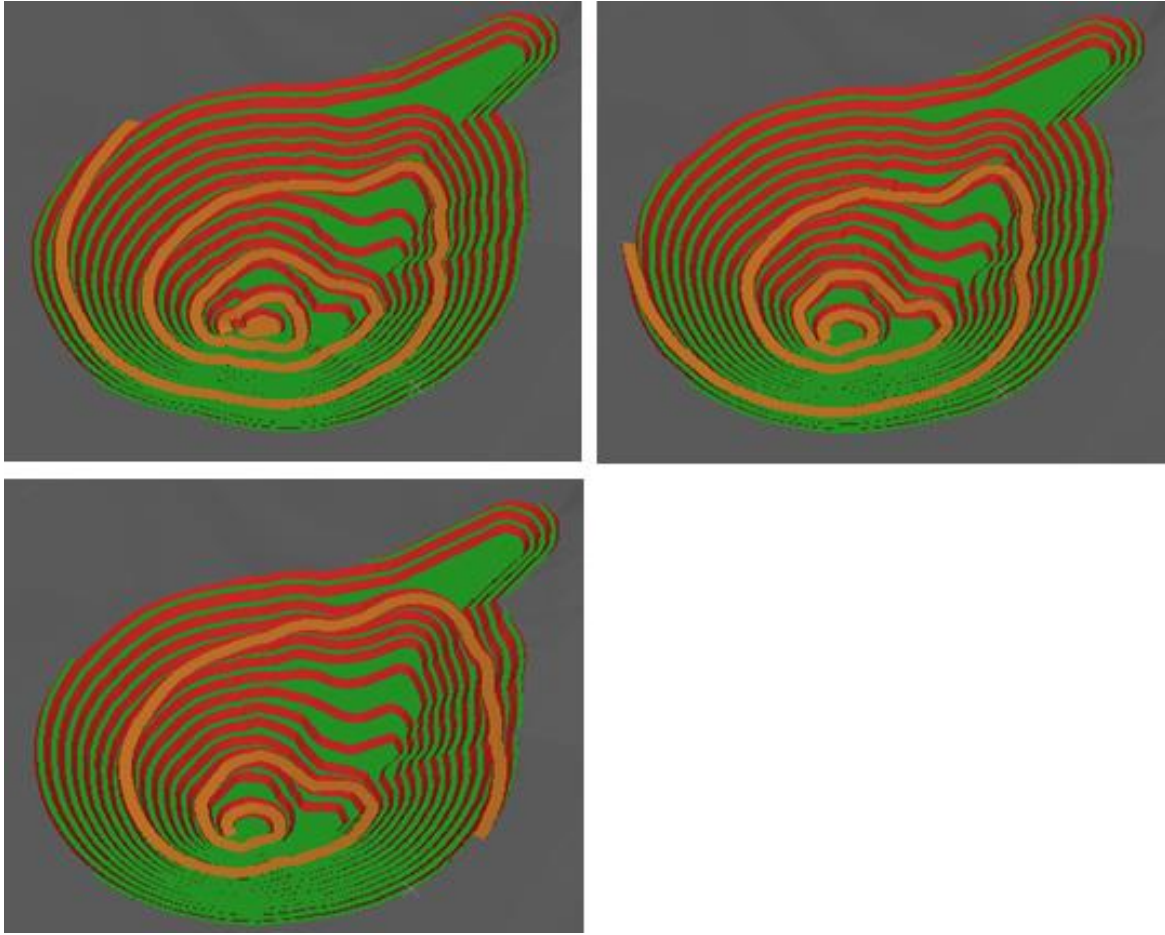
FIGURE 35. DESIGN OF THE LARGE PIT WITH ALTERNATIVE HAUL ROAD GRADE AND A MEDIUM ROAD WIDTH. TOP LEFT 6%, TOP RIGHT 8%, AND BOTTOM LEFT 10% GRADE

Examining Figure 35, it can be clearly observed that changing the haul road grade has a significant impact on not only the pit geometry, but also the haul road length, where a lower grade results in a much longer haul road compared to the steep grade.