Study on the Impact of Trolley Assisted Haul Trucks on Strategic Mine Planning in Open Pit Mines

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by

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Abstract

Trolley assist is a system in which haul trucks in open pit mines are propelled by electric energy along a designated haul road segment. This can lead to high savings on fuel costs, productivity, CO_2 emission and engine life, but is associated with limitations on mine planning. The purpose of this thesis is to determine how trolley assist can be accommodated into strategic mine planning, in view of optimizing the Net Present Value (NPV). This was investigated by assessing the impact of relocating the trolley infrastructure on the mine schedule and NPV, using GEOVIA Whittle for a theoretical case study concerning a Ghanaian gold mine. The outcome of the case study was that a diesel only scenario yielded the highest NPV, meaning that the operational savings of trolley assist were not high enough to offset the required capital investment. The comparison between two trolley assist scenarios with a different time period of trolley line relocation resulted in a slightly higher NPV for the scenario with a delay in movement of one period, relative to the original trolley assist scenario.

To account for the trolley infrastructure in the scheduling process, increased mining cost adjustment factors (MCAF) were used on the trolley line locations. This methodology was found adequate for the Ghana Gold case, but it requires detailed knowledge on the planned (re)location of the trolley infrastructure. It was found that delaying the trolley line relocation by one period only caused minor changes in the mine schedule and operating costs of the Ghana Gold case, justifying the slightly increased NPV for the delayed trolley assist scenario. However, considering the proportion of the total project value, the difference between the NPV's of the assessed scenarios was negligible.

The results of the case study did not deliver enough support for the hypothesis that incorporating trolley assist in the long-term mine plan is key in achieving an increased NPV with trolley assist. Nevertheless, it is clear that the feasibility of trolley assist is not a simple offset between capital investment and operational savings. Most limitations of this research resulted from the complexity of the Ghana Gold block model and the poor availability of detailed cost data.

Keywords: trolley assist, strategic mine planning, haul trucks, open pit mines, scheduling, Whittle, NPV.

Preface

This thesis is submitted as final assignment of the Geo-Resource Engineering program, in order to obtain the degree of Master of Science at Delft University of Technology.

About two years ago, I was introduced to the concept of trolley assist in open pit mines, by Dr. Ursula Thorley of Queen's University, Ontario. The idea of substituting diesel fuel by electricity really appealed to me, both from an economic and operational perspective, as with respect to the global footprint of open pit mines. I was very fortunate to encounter Ard Wormeester, who shared my interest in trolley assist and was able to provide me with this suitable thesis project, accommodated by Caterpillar Global Mining.

I am happy to have spent the last months of my university career working on a project that suited my interests so well, and to conduct research with such a distinct relevance to the mining industry. Although there are still more details that could be investigated to assess the impact of trolley assist on mine planning, I truly hope that this project will contribute to the potential implementation of new trolley assist systems.

M.M.A. Kox
Delft, September 2017

Acknowledgements

Without the guidance and support from many people around me, I would not have been able to produce this thesis. I am very fortunate to have received plenty of help and good advice, and I would like to take some time to express my gratitude to several people in particular.

First of all, I would like to thank my thesis committee for their feedback. Specifically, I want to offer my thanks to my supervisor Ard Wormeester, for providing me with this thesis project and for giving me the opportunity to execute my research as a graduate intern of Caterpillar Global Mining. I am also very grateful for all of his input, especially for sharing his insights and knowledge during our countless phone calls and meetings. I would also like to express my gratitude to Mike Buxton, for his supervision, advice and support throughout the entire project. Without his guidance, this research could not have been successfully conducted.

Thanks to Onno ten Brinke, for providing me with a custom-made case study and the required software, and for taking the time and effort to assist me in the mine planning process. Special thanks to Eric Ruth for providing me with technical and economic details of trolley assist.

Without the hospitality of FQM Operations at Kansanshi in Zambia, I would have never been able to relate the theoretical findings of my thesis to a real-life situation. I am grateful that I got the opportunity to see such an advanced trolley assist system in operation.

Above all, my appreciation goes out to my friends and family, for their moral support during the last few months. In particular, I want to thank Jeroen and Mathijs, whom I could always count upon for advice and discussion during our numerous coffee and lunch breaks.

Last, but not least, I would like to dedicate this thesis to my parents. Thank you for always encouraging me, and for supporting me in achieving my goals.

Contents

1

Introduction

The most common way to transport ore and waste rock in open pit mines, is by using large haul trucks. The haul trucks travel significant distances over mostly inclined haul roads, towards their destination, e.g. a crusher or waste dump. This uphill transport demands a lot of power from the trucks, which is normally generated by a diesel engine. Hence, the transport of ore and waste rock accounts for a considerable amount of the mine's fuel consumption. It also requires a high capital investment in the procurement of large haul trucks. Therefore, hauling ore and waste is a substantial capital expense for the mine. Additionally, the intensive consumption of diesel fuel is a major source of greenhouse gas emission.

Mining operations are always looking for ways to lower their cost per tonne. Reduction of fuel costs and the amount of large haul trucks required, could contribute to a lower cost per tonne. It is already common for loading equipment, such as shovels and excavators, to run on electric energy, but electrification is less often applied to the haulage circuit. By using electric energy rather than diesel power to propel the truck, the fuel consumption will decrease and the emission of exhaust fumes will decline. Furthermore, haul trucks driving on electricity can achieve higher uphill speed. A suitable way to provide heavy-duty vehicles with electric energy, is by overhead power lines. This system is called trolley assist, roughly comparable to electric (trolley) trains or trams. [1–3]

The potential benefits that a trolley assist system could deliver, are dependent on its suitability within strategic mine planning. Mine planning is a key factor in the feasibility of an open pit mine. A mine plan determines which parts of the mine are extracted at what time, with the aim of maximizing the profit of the operation. It is a complex and iterative process, taking into account different time-dependent or uncertain factors, such as commodity price, production limit and ore grade. By adding the trolley system element to the operation, additional requirements regarding infrastructure, material movement, and operating and capital costs will occur. It is critical that the installation and operation of a trolley line fits into the mine plan, or that the mine plan can be adjusted accordingly. [1, 2]

Currently, there are only a few open pit mines that use trolley assisted haul trucks. According to Gerdts [2], mining companies are hesitant to implement a trolley system, because they are unfamiliar with the system and its potential benefits. It is a common assumption that trolley assist comes with high capital costs, resulting in a long payback period. Furthermore, trolley assist is often associated with high maintenance costs.

In order to achieve savings on the cost per tonne, the operational benefits of the trolley assist system should outperform the limitations on mine planning. In this thesis, the impact of trolley assist on mine planning will be analyzed, as well as the potential benefits of operating the system. By means of a case study, it will be investigated if there is a suitable mine planning methodology when implementing trolley assist. As stated by Gerdts [2], there is still a lot of ambiguity amongst mining companies when it comes to trolley assist. By assessing and applying the impact of trolley assisted haul trucks on mine planning, this thesis could give more clarity about the suitability of a trolley system for specific open pit mines.

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Objective & Scope

In the following chapter, the research motivation, objective and methodology for this thesis will be introduced and the report outline will be presented.

2.1. Hypothesis

In the past, successful trolley implementation mainly occurred at mining operations in Southern Africa. Today, trolley systems are considered for a broader range of (future) mining operations, implying that trolley technology has changed, or that the industry is looking for alternative approaches towards the conventional way of open pit mining.

Implementation of a trolley system can increase the Net Present Value (NPV) of open pit mining operations. It is known that when the trolley system is installed and operational, the energy cost is reduced and the production rate increases. However, trolley assist also comes with extra logistical and infrastructural requirements, and therewith associated costs. [1–4]

To provide a feasible trolley application, an offset of the expected savings against the extra investment and requirements has to be made. This means that savings on the energy cost and benefits of the increase in productivity have to be weighed against the capital costs and the impacts on the long-term mine plan. The latter includes the impact of trolley line installation on the ramp design, stripping ratio, pushback selection and the life of mine. The hypothesis is that incorporating the benefits and limitations of trolley assist in the optimization of the long-term mine plan is a key factor in achieving an increased NPV with trolley assist.

2.2. Objective

The aim of this thesis is to determine how trolley assist in open pit mining can be accommodated into strategic mine planning, in view of optimizing the NPV. This includes balancing the frequency of the movement of the trolley infrastructure against the savings generated from operating a trolley system, for a specific case study.

Caterpillar has a trolley assist system available on the 795F AC haul truck. To provide customers with the best service, Caterpillar is interested in understanding the impact that trolley assist has on the operation, specifically in relation to mine planning. Understanding this impact can help identify potential customers for a trolley fleet, as Caterpillar can assess the feasibility of trolley assist and inform the customer about the possibilities of enhancing their performance by choosing for trolley assisted haulage.

2.3. Research Questions

The hypothesis and objective have led to a number of research questions, that form the core of this thesis.

1. What is the "new" trolley technology that increases the favorability of future trolley implementation?

2. What are likely costs for trolley implementation, with respect to capital investment, and operating and moving the system?
3. What are extra requirements for infrastructure, maintenance and logistics for trolley implementation?
4. What are the savings generated with trolley assist, where does it occur in the process and how is it realized?
5. By means of a case study, how does trolley assist affect mine planning?
    (a) What is the impact on the planning process?
    (b) What are the requirements for revised mine planning?
    (c) What is the sensitivity of trolley implementation to (geo)technical, geologic and economic deviations?

2.4. Methodology

The feasibility of trolley assist and its fit into the mine plan are indissolubly dependent on the characteristics of the operation, which makes it difficult to define a generic approach to the objective. Therefore, for this thesis a case study is used to assess the impact of trolley assist. The case study concerns a theoretical, active open pit gold mine in Ghana. The case study is approached with the intermediate pit as starting point, and the final pit has already been designed. Software used for this case study are GEOVIA GEMS, GEOVIA Surpac, GEOVIA Whittle and Caterpillar FPC. By considering different scenarios with respect to the period of moving a trolley line within one pushback, the optimum NPV with trolley assist will be sought. Based on the outcome of this assessment, conclusions regarding the impact of incorporating trolley line benefits and limitations on strategic mine planning are drawn.

2.5. Scope

This thesis covers the impact of trolley assisted haul trucks on strategic mine planning. Background information related to trolley assist and strategic mine planning is required for an appropriate understanding of the subject. Furthermore, the scope of this research is comprised of the following topics:

- cost model preparation in Excel;
- case study model preparation in GEMS and Surpac;
- scheduling in Whittle;
- sensitivity analysis on the NPV against electricity cost, diesel cost, commodity price, ore grade and utilization;
- definition of generic suitable scenarios for trolley assist;
- influence of trolley assist on the width of the ramp
- assessment of time of trolley line movement, cost of the line movement and utilization of the system.

Due to the limited amount of time available to this research, the following topics were a priori excluded from the project's scope:

- developing a generic mine planning methodology;
- a scenario with an in pit crusher;
- orebody modeling;
- extensive schedule optimization;
- multiple movements of the same trolley line segment;
- assessment of auxiliary equipment and mining processes;
- seasonal constraints.

2.6. Outline

The report is structured in three phases, being a literature review, case study and synthesis. The literature review contains in-depth background information on the concept of trolley assist and strategic mine planning. The case study is the central part of this thesis, comprising the applied research on the Ghana Gold case and a sensitivity analysis on a number of key parameters. In the synthesis, the findings of the case study will be examined in view of the literature review, resulting in final remarks and recommendations. The three phases are represented by nine chapters, as outlined below.

Literature Review

- **Chapter 3**: *The Application of Trolley Assist in Open Pit Mining*
  Gives an overview of the fundamentals of trolley assist, the historical background and associated benefits and limitations.
- **Chapter 4**: *Strategic Mine Planning*
  Explains the theoretical background of strategic mine planning.

Case Study

- **Chapter 5**: *Case Study*
  Describes the work done during the Ghana Gold case study, including presentation and interpretation of the results.
- **Chapter 6**: *Sensitivity Analysis*
  Discusses the influence of a set of key parameters on the NPV.

Synthesis

- **Chapter 7**: *Discussion*
- **Chapter 8**: *Conclusion*
- **Chapter 9**: *Recommendations*

3

The Application of Trolley Assist in Open Pit Mining

Over the last few decades, a small number of open pit mines have installed and operated a trolley assist system. To assess the potential of trolley assist today, a lot can be learned from analyzing the trolley assist systems of the past. This also requires a basic understanding of the operational principle of trolley assist, and the associated costs and benefits of installing and operating the system. The following chapter introduces the fundamentals, development and characteristics of trolley assist.

3.1. Fundamentals

In conventional open pit mining operations, haul trucks are equipped with a mechanical drive system. This drive system is based on a mechanical drivetrain, which transmits the torque generated by the engine to the wheels. The drivetrain includes components such as a transmission (or gearbox), differential, final drive shafts and a mechanical torque converter. According to Koellner et al. [5], mechanical drive haul trucks can be a cause of high maintenance and repair costs, because of the complex drive system. The speed of mechanical drive trucks is limited by the maximum power that can be generated by the diesel engine. [5, 6]

Another option for haul trucks in mining is a diesel-electric drive system. Within this system, the wheels are driven by electric traction motors, that receive electric energy from the alternator. The alternator is powered by the diesel engine. The use of a diesel-electric system eliminates the complex mechanical drivetrain components, which, as stated by Chadwick [6], increases the performance and reduces maintenance and repair costs. However, since the alternator is powered by the diesel engine, the truck speed is still limited to the maximum diesel engine power. Therefore, it is not more efficient than a diesel driven mechanical drive system. [5, 6]

When using diesel-electric drive trucks, a trolley assist system can be implemented to substitute energy from the diesel fueled alternator by electric energy. Overhead power lines deliver electric energy to the truck, directly transmitting electric power to the traction motors and hence bypassing the diesel engine. When bypassing the diesel engine, the speed of the truck is no longer limited to the maximum power generated by the diesel engine, resulting in higher output ratings of the electric drive components. As the diesel engine still delivers power to the hydraulic and cooling system, it is not switched off entirely. When on trolley assist, the diesel engine operates at low rpm (idling). The overhead trolley lines are able to deliver more power than the on-board power source, which means that the output of the traction motors can be maximized. Equation 3.1 shows that a higher power rating leads to a higher potential speed. Hence, with increased traction motor output, a higher truck speed can be achieved. [2]

$$
\begin{aligned}
v &= \frac{Power}{Rimpull} \\
&= \frac{P}{GVW * 9.81 * Grade}
\end{aligned}
\tag{3.1}
$$

where:
v = speed in m/s
P = power in kW
GVW = gross vehicle weight in t
$Grade$ = effective grade in %

Trolley assist systems typically are associated with productivity, cost and environmental benefits. Based on results achieved by mining operations with trolley assist the following benefits are evident [1, 4, 5, 7, 8]:

- With the diesel engine at idle when on trolley assist, the amount of diesel fuel burnt by the haul trucks is reduced considerably. Not only does this lead to a significant cut in fuel costs, it also decreases the emission of exhaust gases and therewith associated air pollution.
- By bypassing the diesel engine, the power delivered to the traction motors is no longer limited by the diesel engine. The electric traction motors have a higher output than the diesel engine and therefore the haul trucks will be able to achieve higher speed, depending on the capacity of the wheel motors. This result is especially noticeable on uphill ramps when loaded, when the traction motors require the largest amount of power.
- Because the haul trucks operate at a higher speed, the productivity per truck increases. This translates into a higher production capacity of the mine and a potential reduction in truck fleet size.
- Additional to the higher speed, the increased power of the traction motors also enables haul trucks to achieve higher gradients. Therefore, compared to mechanical drive trucks, higher grade haul roads can be used and deeper parts of open pit mines can be reached more easily.
- The decreased use of the diesel engine results in an increased life time of the engine, extending the number of hours between maintenance or overhaul.

Despite the above listed benefits, only a few mining operations employ trolley assist systems. The success of trolley implementation is heavily dependent on mine specific factors, such as the difference in cost between electric power and diesel fuel, size of the mine and long-term mine planning. Additionally, the installation of a trolley assist system requires significant capital investment. Therefore, designing an efficient strategic mine plan is key in achieving a successful trolley assisted operation with optimal Net Present Value. [1, 5]

3.2. Historical Background

The first application of a trolley system on vehicles other than trains dates back to 1882, when Werner von Siemens developed a trolley bus in Berlin. Following this development, the trolley technology was further improved and applied on a broader range of equipment.[9] Table 3.1 lists the open mining operations that operate or have operated with trolley assisted haul trucks.

3.2.1. Industrial Application

In 1938, the first industrial application of trolley systems was established at the Valtellina Dam project in Italy. The trucks carrying cement for the construction of the dam, were completely powered by electric energy from overhead power lines. Around the same time, in 1939, electric trolley trucks were developed for use at the River Rouge underground mine in Michigan (USA). Similar to the trucks at Valtellina, these trucks were fully electrical. When not connected to the trolley line, the small trucks were powered by a battery. [9]

In 1967, Kennecott Copper Corporation was the first company to investigate the possibility of using trolley assist on large haul trucks in open pit mining at the Chino mine in New Mexico (USA). Unlike the previous

Table 3.1: Overview of open pit mines that operate or have operated trolley assist. Based on data obtained from Gerdts [2], Admill [3], Hutnyak [9], Chadwick [10].

Mine	**Country**	**Commodity**	**Trolley Installed**	**Status**
QCM Lac Jeannine	Canada	Iron Ore	1970	Operation ceased, 1977
Palabora	South Africa	Copper	1981	Open pit operation ceased, 2002
Sishen	South Africa	Iron Ore	1982, AC in 2008	Operational
Nchanga	Zambia	Copper	1983	Trolley decommissioned, 1990's
Grootegeluk	South Africa	Coal	1983, AC in 2001	Operational
Rössing Uranium	Namibia	Uranium	1986	Operational
Goldstrike	USA	Gold	1994	Trolley decommissioned, 2001
Lumwana	Zambia	Copper	2009	Trolley decommissioned, n.d.
Kansanshi	Zambia	Copper	2012	Operational
Sentinel	Zambia	Copper	2017	Operational

industrial applications, this experiment combined the diesel engine with electric wheel motors, creating the foundation for the trolley assist system as it is today. The feasibility study proved that a trolley assisted truck could achieve a higher speed. However, the system was never fully implemented. [9]

Although the Kennecott experiment was successful in terms of technical feasibility, there was only one other mining operation that investigated the possibility of trolley assist before the 1980's. Followed by a prosperous feasibility study and test period, the Québec Cartier Mining Company started operating a trolley assist system in their open pit mine at Lac Jeannine (Canada) in 1970. As opposed to the Chino experiment, the Lac Jeannine study did not only look into the technical feasibility of the trucks, but focused on the overall trolley assist system. There was more attention for the power distribution system, and the study considered a full trolley fleet rather than a single truck experiment. The trolley assist system was successfully used for approximately seven years and ceased when the mine closed in 1977. [9]

3.2.2. The 1979 Oil Crisis

The oil crisis that marked 1979 and 1980 (see Figure 3.1) led to a significant price increase in diesel fuel. According to Mazumdar [8], the oil crisis was the main driver in studies on and development of new trolley assist systems for open pit mines. Especially mining operations in Southern African countries implemented trolley assist during the years following the '79-'80 crisis (see Table 3.1). Due to the oil embargoes in Southern Africa during the 1980's, electricity was significantly cheaper than diesel and therefore trolley assist was an economically favorable option to reduce cost per tonne for large open pit mining operations. [12]

3.2.3. Renewed Interest

Apart from the installation of a trolley system at Goldstrike (USA) in 1994, the interest for trolley assist seemed to fade away. By the end of the previous millennium, AC (alternating current) diesel-electric trucks were developed. Before that time, electric-drive haul trucks operated on DC (direct current) configuration. In section 3.4.1, the difference between AC and DC drives will be further explained. During the 2000's, the AC drive technology kept on improving for larger haul trucks. In Table 3.1 it can be seen that the first generation of mines with trolley assist occurred in the 1980's and that, apart from the Goldstrike mine, the next generation followed more than 20 years later. Additional to the new trolley operations in the 2000's, the Grootegeluk and Sishen operations improved their trolley system with AC technology in 2001 and 2008 respectively. [3]

The renewed interest in trolley assist of the last decade is likely due to multiple reasons. Mining companies aim to reduce their diesel fuel consumption because of economic considerations. In Figure 3.1 it can be seen that the oil price experienced a significant increase during the first decade of the 2000's. The oil price also

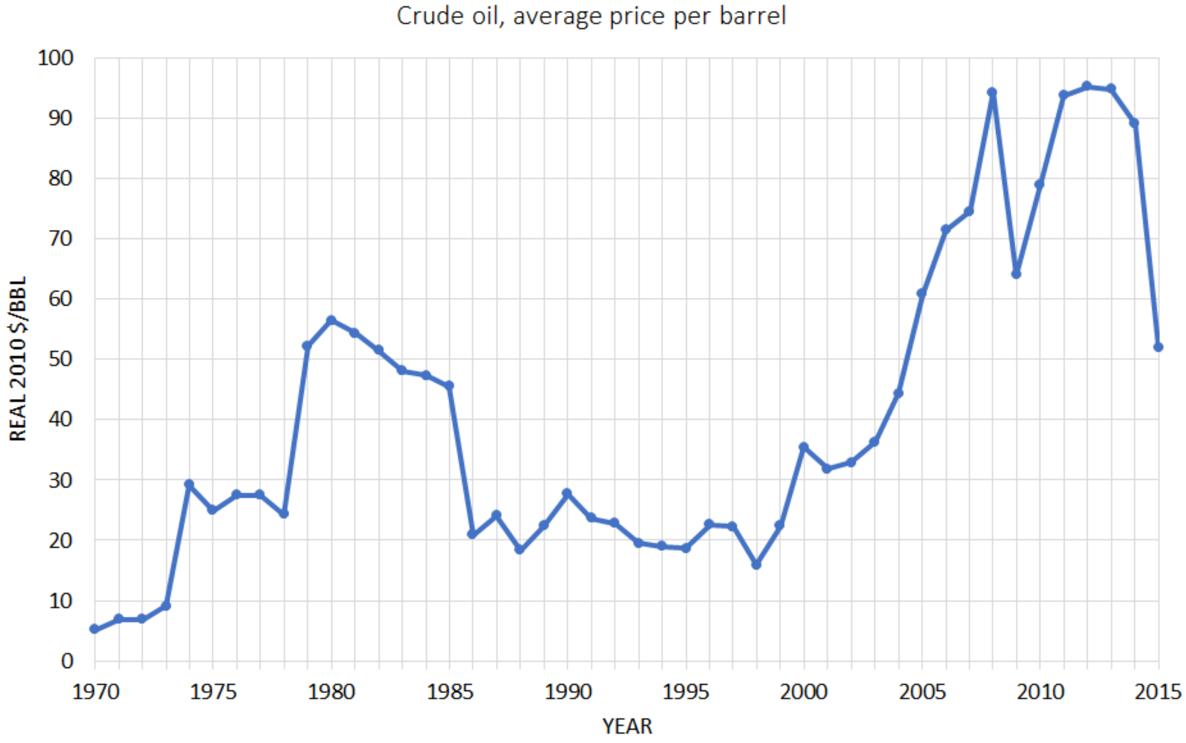


Figure 3.1: Average crude oil price per barrel between 1970-2015, in real 2010 US dollars. Based on data obtained from The World Bank [11].

shows heavy fluctuations over the last 10 years, imposing a high level of uncertainty on mine economics. The increased public awareness of CO_2 emission contributes to the diesel fuel reduction incentives as well. [8]

Another reason could be that the newer AC haul trucks are considerably more powerful than the diesel-electric haul trucks used in the 1980's, increasing truck performance and the potential to lower the cost per tonne of an operation. More existing truck models become available with a trolley compatible drive system, increasing potential for new trolley assist projects. Furthermore, the exploitation of deeper, more marginal deposits nowadays forces mining companies to look for more expenses to cut back. Since the operating cost of a haul fleet is a large expense, alternative haul systems like trolley assist could be an adequate saving for operations in these challenging deposits. [5]

3.2.4. Geographical Preference & Geological Conditions

From the list in Table 3.1, it is evident that the majority of trolley assist operations are located in Southern Africa. Whereas the trolley technology has its roots in the USA (Chino mine, 1967), only two of the ten listed operations are outside Africa. As discussed in section 3.2.2, the original presence of trolley assist in Southern African mines was predominantly due to the high difference in diesel and electricity prices. This difference was not as profound in the rest of the world, which could be the main reason why trolley assist was not implemented in European and Australian mines.

From Table 3.1, it can be concluded that the suitability of trolley assist is not dependent on a solemn commodity or deposit type. Successful trolley assist systems have been implemented in e.g. pipelike copper deposits (Palabora) [13], massive iron ore deposits (Sishen) [14], interbedded coal seam deposits, varying in thickness (Grootegeluk) [15], large, low grade uranium deposits (Rössing) [16], massive hydrothermal gold deposits (Goldstrike) [17] and high angle copper veins (Kansanshi) [18]. According to Janusauskas et al. [1], the feasibility of a trolley assist system is mostly dependent on the economic climate, mine life, productivity and mine plan amenability rather than on geological conditions.

3.3. Trolley Configuration

The implementation of a trolley assist system brings along additional installations on diesel-electric haul trucks and haul roads, compared to conventional open pit operations. In this section, the configuration of on-board truck hardware and wayside equipment related to trolley assist will be discussed.

3.3.1. On-board Hardware

The most distinct addition to haul trucks are the two pantographs that are mounted to the front of the truck. The pantographs serve as a conduit between the trolley line and the DC link. Therefore, proper contact between the pantograph and the overhead line is key to a successful trolley connection. This requires additional skill from the operator, who has to position the truck under the line. Visual aids, such as small flags on the pantographs, are being used to assist the operator. More advanced position sensors that can be connected to an on-board monitor are being developed. Because of the bouncing motion of the truck, the brushes on the pantographs are designed to withstand a limited amount of movement in order to keep contact with the line. Nevertheless, when using trolley assist, adequate maintenance of the haul roads is still a key factor in achieving optimal utilization. [2]

The haul truck is also equipped with a trolley box, which contains control devices that enable the internal power circuit to bypass the diesel engine. Electric energy is transmitted from the overhead lines to the trolley box. If the detected line voltage is sufficient, the system will switch the power supply from the diesel engine to the overhead lines. This is done by changing the electrical connections of the truck's power circuit. [5]

3.3.2. Wayside Equipment

In Figure 3.2, a part of the wayside installation at the Kansanshi mine is shown. The following section describes the key components, as indicated in Figure 3.2.

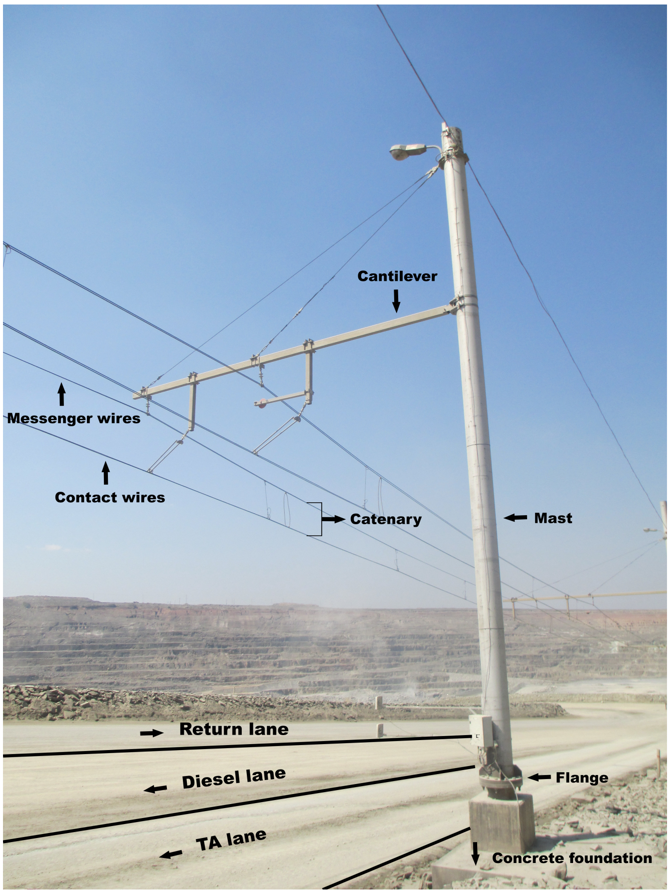


Figure 3.2: View on part of the trolley line segment at the Kansanshi mine, Zambia.

The overhead trolley installation requires two conductors. These are represented by two parallel catenary lines. One line serves as positive conductor for the traction current and the other is the negative conductor for the return current. Both lines consist of four wires: two copper contact wires and two copper messenger wires. Depending on the power source, the overhead lines provide the trucks with 1800 V or 2600 V DC. Adequate tensioning of the lines assures an even distribution of power in the catenary lines. The mast poles carrying the lines (by means of a cantilever), are placed at a maximum of 40 meters apart. The mast poles are anchored to the ground with concrete foundation blocks. The size of the concrete blocks is dependent on the ground conditions.

Part of the concrete foundation is poured directly into the ground, making it a permanent foundation. On top of this permanent base, a smaller concrete block is placed, which can be moved (indicated by the arrow in Figure 3.2). There are fixed catenary systems, that stay in place the entire mine life, and mobile catenary systems that can be relocated. The masts are mounted to the foundation with a flange and anchor bolts, which allows for easy mast removal in case of damage or relocation. [pers. comm., Ruth, 2017a], [3, 4]

The overhead lines are fed by substations. The substation determines the voltage and power of the overhead lines, as well as how many trucks can engage to an overhead line segment simultaneously. Each trolley segment requires at least one substation. Depending on the voltage and number of trucks engaged to the line, a substation is required every 400-800 m. The main components of a trolley substation are a transformer, rectifiers and AC/DC switchgear. [1, 3, 19]

Typically, substations are connected to electricity networks ranging from 6 to 30 kV, with an output power ranging from 2.5 to 10 MW. [20] AC drive systems perform best at 2600 V, compared to older DC drives at 1200 to 1600 V. [7] Therefore, development of more powerful, efficient and safe substations is a significant contribution to the innovation of present-day trolley technology. For example, nowadays a 10 MW substation can deliver a voltage of 2600 DC as opposed to the 1200 V DC that was generated by a 5 MW substation in the 1990's.[19]

3.3.3. Direct Trolley Operation

Direct trolley operation is used when the overhead line voltage delivers sufficient power to feed the 2600 V AC drive haul truck. When on direct trolley operation, the electrical energy of the overhead line yields 100% of the power required in propel mode. As the truck engages to the overhead line, the DC link is connected in parallel with the line. Hence, compared to the original circuit only the DC link and inverters remain included. The diesel engine, alternator and rectifiers are excluded from the circuit. [5, 7]

3.3.4. Diesel Boost Trolley Operation

Diesel boost trolley operation is used when the overhead line voltage is lower than the AC drive system operating voltage. In most scenarios, this occurs when a mine has already operated DC haul trucks on lower voltage trolley lines. During diesel boost trolley operation, both the overhead lines and the diesel engine supply power to the DC link. Combined, they can deliver the required power for the AC drive system with considerably less fuel consumption. When the truck engages to the overhead line, the line is connected in series with the rectifiers, which in turn are connected in parallel. Hence, compared to the original circuit all components are included, but the rectifiers are connected differently. [5, 7]

3.4. Innovative Technologies

As discussed in section 3.2, the installation of trolley assist systems in open pit mining occurred in waves. The biggest driver for the initial application of trolley assist was the oil crisis in the 1980's. The second wave occurred around the 2010's and was mainly driven by the aim to reduce mining costs. The recent renewed interested in trolley assist systems is likely because of a better flexibility of the system on different aspects, as a result from innovative technologies in trolley assist. These new or improved technologies will be discussed in the following section.

3.4.1. AC Drive Systems

By the end of the 1990's, haul trucks with AC (alternating current) drive systems rather than DC (direct current) drive systems for haul trucks were developed. According to Koellner et al. [5], this was due to the demand for larger trucks in open pit mining operations. Haul trucks with a higher capacity require more power and it was not feasible to develop DC drive systems for these demanding trucks anymore. Haul trucks with a capacity over 240 short tons required more powerful, AC driven traction motors.[5]

The power generated by the diesel engine is converted into AC power by an alternator. This current is then converted into DC power at a constant voltage, in a rectifier. Next, the DC power is converted back into AC power by two separate inverters. The current is now in a controllable condition, with variable voltage and frequency. The AC power from the inverters is fed into both traction motors to create the speed and torque required for propulsion of the haul truck. [21]

Many advantages of AC drives over DC drives are related to the squirrel cage induction motors, which are driving the wheel gears. The squirrel cage induction motors eliminate the presence of DC commutators. This results in higher possible speed, lower maintenance, increased reliability and better efficiency. [7]

AC drive haul trucks operating on trolley have advantages over DC drive haul trucks. AC trucks can connect to and operate on the overhead power lines at any speed, because they are independent on the line voltages. This is opposed to heavy, overloaded DC trucks that can sometimes have difficulties connecting to or operating on the overhead power lines due to slow speed, causing the truck to be rejected. AC trolley assisted trucks can also handle a wider range of line voltages and are therefore less subdue to power fluctuations. [7]

3.4.2. IGBT Technology

A recent development in AC drive systems is the IGBT (Insulated Gate Bipolar Transistor) inverter technology, creating additional benefits to the conventional GTO (Gate Turn-Off Thyristor) technology for AC drives. IGBT modules have simpler and smaller gate driver circuits. This highly increases reliability and efficiency of the drive system, and accommodates a higher overload capability. [5, 7]

3.4.3. Retarding & Braking System

AC electric drive trucks operate an electric retarding system. During electric retarding, the traction motors generate kinetic energy, which is converted into AC power and next into DC power by the IGBT modules within the inverters. Braking choppers are linked to the inverters and channel the generated power into the resistor grid. The resistor grid dissipates the energy in a continuous way, decreasing voltage generated by the traction motors and hence decreasing speed. This electric-dynamic retarding system is designed to deliver a smooth braking process, at higher speeds than mechanical or DC drive trucks. [5, 22]

With the electric-dynamic retarding system, the electric retard is blended out when the truck speed approaches zero. Simultaneously the service brake is blended in, enabling the operator to use the service brake in the last part of the braking process. [5] According to Mirzaei and Fernandez [22] this system is advantageous for high speed retarding, but the forced use of the service brakes poses higher costs for maintenance and repair of these brakes. Therefore, Caterpillar combined the electric-dynamic retarding system with their mechanical brake system, by installing four corner wet disc brakes alongside the electrical retard. When the electric-dynamic retarding capability reaches its maximum, the mechanical brake system is smoothly blended in. The use of the service brake to come to a complete standstill is not required anymore. The electric-dynamic retarding system is also advantageous in slippery conditions, offering increased traction control. [22]

Further steps are being taken to use the energy generated by the retarding process, instead of dissipating it into the air by the resistor grid. For example, the energy could be used by other, less powerful equipment in the mine (because the voltage is too low to use for haul trucks) or fed back into the utility grid. [8]

3.5. Requirements

As stated in section 3.1, the operation of a trolley assist system does not solely come with productivity, cost and environmental benefits. The success of trolley, being an increased NPV, is heavily dependent on mine specific factors and installation and operation of the system comes with extra requirements compared to conventional haulage systems. In this section, general additional requirements for electrical infrastructure, haul roads and equipment maintenance with trolley assist systems will be discussed.

3.5.1. Electrical Infrastructure

The electrical infrastructure consists of distribution lines (mine power distribution), substations, catenary lines and mast poles. The electrical infrastructure is the main contributor to high capital costs and the limited mobility of the trolley system. The three-phase medium voltage (MV) distribution lines link the substations along the haul road with the main power station. The substations transform the MV electricity into the power required by the overhead wires, for example 2600 V DC. In order to achieve a high availability of the trolley line, a reliable source for electricity is of high importance. [5, 19]

3.5.2. Haul Roads

Maintenance of haul roads is a key factor in achieving a successful connection between the truck's pantograph and the overhead wires. Pantographs are designed to withstand a limited amount of movement, but significant motion will prevent the truck from connecting to the wire, or cause damage to the electrical infrastructure when it remains connected (i.e. arching of the wires). Therefore, it is of high importance to keep the haul road well maintained, i.e. constant grades and smooth surfaces without debris or ruts. A failing connection can also cause damage to the pantograph (brushes). Repairing the pantograph will cause down time for the truck and therewith associated costs. Damage to the wire can cause significant financial impact, when the trolley system is unavailable due to wire repairs. [1]

Compared to conventional operations, a trolley assist system could lead to an increased width of the haul roads. To minimize delays due to limited utilization of the trolley line, ideally an extra lane should be available. This allows trucks operating on trolley to take over trucks that are not operating on trolley. Limited utilization of the trolley line could occur due to maintenance or repair on the wires or pantographs, but usually occurs due to the maximum amount of trucks that can engage to the line simultaneously. However, adding an extra lane to the haul road means an increase in waste material mined, or a lower ore recovery and could thus have major financial impact. The addition of an extra lane is not required, a dual or even a single lane haul road are also possible. The best suitable haul road design depends on the operation. In either way, the width of the haul road needs to be increased due to the additional electrical infrastructure. [1]

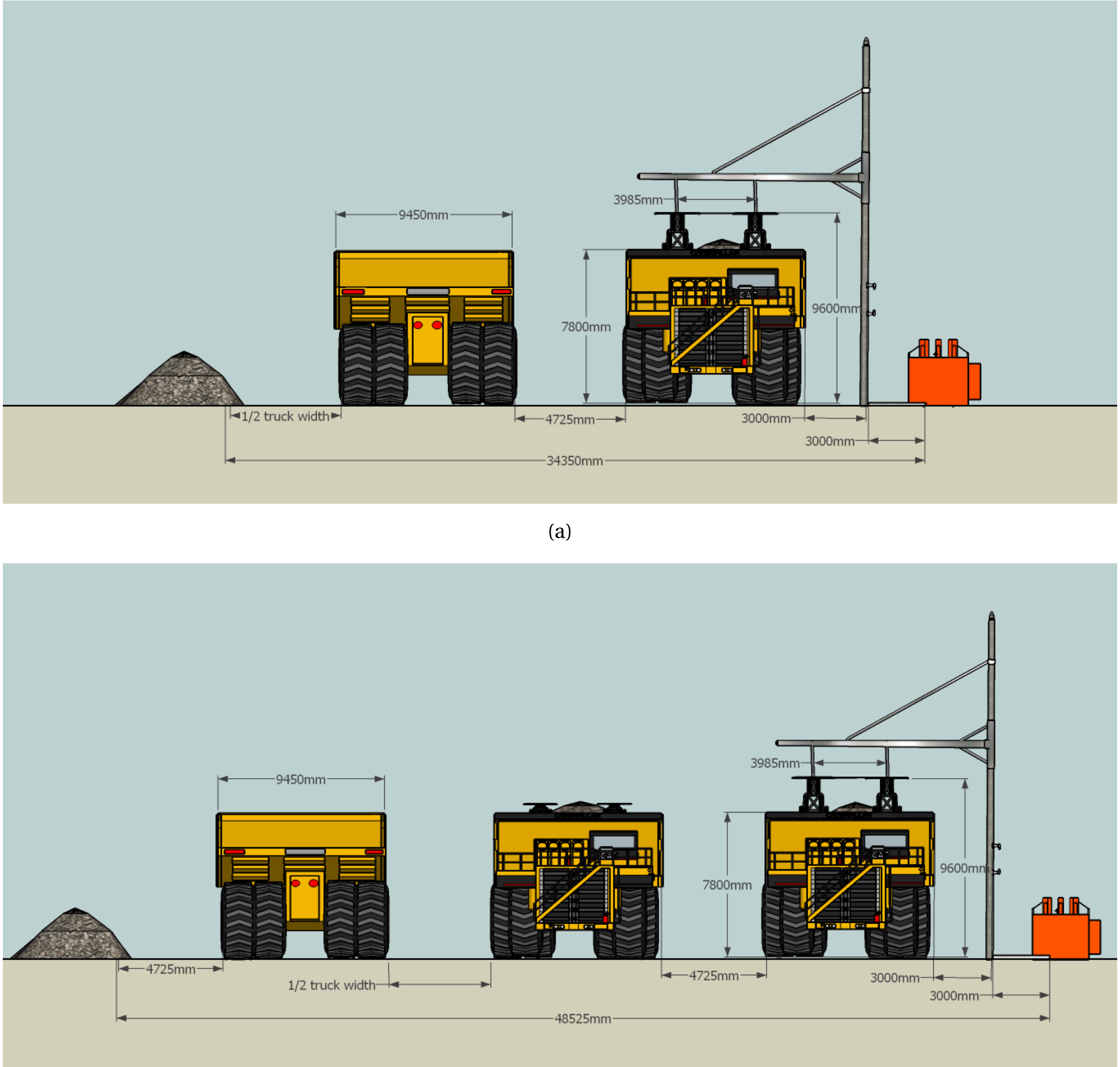
Figure 3.3 shows typical haul road configurations for a dual and triple lane with Cat 795F AC haul trucks on trolley assist, including the minimum widths for these configurations. In this representation, the space between the trucks is $\frac{1}{2}$ truck width (haul road width factors are further discussed in section 4.4). The minimum distance between the mast and truck is 3 meter. On the right side of the mast, there is another 3 meter for the foundation block. The substation is shown in orange, but is not accounted for in the minimum width, since it does not occur along the entire trolley line segment. It could be positioned on the bench above the haul road for example. Therefore, it does not necessarily affect the haul road width, depending on the ramp design. Both configurations in Figure 3.3 do not include the width of the safety berm and gutter or drain. Hence, the total width of the ramp will be more than the minimum haul road widths from these cross-sections, depending on the ramp design.

3.5.3. Equipment Maintenance

The presence of complex electrical infrastructure poses increased risk for the mining operation. Maintenance of the overhead wires, such as tensioning, is critical to the success of the operation and requires additional skilled labor, as does the maintenance and repair of AC drive trucks. This means that mechanics with additional (electrical) skills, such as proficiency with electric drives, are needed. Since most open pit mining operations are located in remote areas, with limited access to skilled labor, hiring work force with sufficient proficiency could pose additional challenges. [1], [pers. comm., Stott, 2017a]

The reduced wear on the diesel engine decreases the engine maintenance costs of the trucks. The engine life can be expressed in liters of fuel burned, which will be lower in case of trolley assist than with conventional trucks. This means that typically, trolley assist is accompanied by longer engine life and delayed engine overhaul, changing the hourly maintenance and repair rates of the truck. [8]

Offset against the prolonged life time of the engine, trolley assist on a grade poses more strain on other components of the truck, such as the final drive, the tires and the wheel motors. Maintenance and repair rates for these components will likely increase, potentially neutralizing the gain on engine maintenance and repair. On a flat, the increase in strain is significantly less, but typically trolley assist on a flat comes with



(a)

(b)

Figure 3.3: Haul road configuration for a Cat 795F AC haul truck with trolley assist. a) Cross-section of a dual lane haul road, minimum width is 34.5 meter. b) Cross-section of a triple lane haul road, minimum width is 48.5 meter.

little to no gain on speed and productivity. Therefore, trolley assist is usually not installed on a flat, since it becomes more difficult to earn enough savings to payback the capital costs of the system.

Because of the reduced haul truck fleet size the availability of the trucks and of the trolley line is of higher importance compared to conventional operations. When the haul trucks are forced to operate on diesel mode due to unavailable trolley lines, their cycle time will increase and since there is a smaller truck fleet, the production rate might fall short. Hence, efficient maintenance and repair of the trucks, the overhead wires and substations is key in achieving the highest availability possible. [1]

3.6. Costs

According to Gerdts [2] the perception of high capital costs and high maintenance costs are two of the main reasons why only a few mining operations have implemented trolley assist. Capital costs and operating costs are dependent on the mine specific characteristics, such as location and size. The purpose of this section is to identify the typical expenses for a trolley assist system and to give cost indications from previous and current operations.

3.6.1. Capital Costs

Capital costs are expenses for tangible and intangible goods or services that occur once, usually at the beginning of the project. Capital cost estimation is a critical part of a project's feasibility. Typical key capital expenditures for an open pit mining operation are site construction, infrastructure, the processing facility and equipment purchase.

With trolley assist, additional capital costs for site construction, infrastructure and equipment purchase will occur. Adding more capital cost inputs with uncertainty (all costs are estimates), poses more risk for a project's economic feasibility and will affect the NPV. Therefore, assessing trolley related capital costs as detailed as possible is key in evaluating the impact of trolley assist on project economics.

Capital costs for trolley assist are usually expressed as a function of length of the overhead line. Capital expenditures related to trolley assist can be divided in three categories: wayside installation, power distribution system and trolley truck modification. Wayside installation consists of material and installation costs for the initial placement of a trolley line and masts. The power distribution system includes costs for the in-pit power infrastructure, consisting of a main AC substation (outside of the pit) and DC substations along the trolley line. Typically, the main AC substation is already present in a conventional mining operation, since it also supplies other machinery and processes with electricity. The trolley truck modification category covers the adjustments that need to be made to the trucks, assuming that the trucks are electric drive. This includes material and installation of the trolley box and pantographs.

Critical for trolley assist is the offset between typical capital costs related to the system. While the installation of the trolley infrastructure imposes additional capital expenditure, the increase in truck productivity could result in a significant decrease in haul truck fleet requirements. With each haul truck being a multi million expenditure, this will have a positive impact on the capital costs. Table 3.2 lists past practice capital costs as found in literature.

Table 3.2: Overview of obtained capital costs for trolley assist systems. Costs in 2017 US$. Data obtained from Janusauskas et al. [1], Brodkorb [20].

Expenditure	**Minimum cost**	**Maximum cost**	**Average cost**	**Unit**
Trolley line installation	1,100,000	3,610,000	2,200,000	$/km
Main AC substation	360,000	4,560,000	2,460,000	$/unit
DC substation installation	720,000	2,040,000	1,400,000	$/unit
Truck modification	300,000	580,000	410,000	$/unit

3.6.2. Operating Costs

Operating costs are expenses that occur on a regular basis, as opposed to capital costs which are set items that occur once. Operating costs can be fixed or variable (changing over time), and are usually expressed in dollar per tonne. Mining operations aim for minimum operating costs, to ensure the lowest cost per tonne and maximize profit. Typical key operating cost items are divided into mining costs, milling costs, selling costs and general and administrative (G&A) costs.

With trolley assist, predominantly the mining cost share of the operating cost will be affected. Additional to the reduction in truck fleet, a decrease in operating costs is usually one of the goals of a trolley assist system. The reduction in fuel consumption will decrease fuel costs, but the use of electrical power will increase electricity costs. The potential gain on energy costs is therefore dependent on the difference in diesel fuel price and electricity price. A rule of thumb is that break-even point of trolley assist on energy costs occurs when the ratio between electricity price and diesel fuel is approximately 1:5 [pers. comm., Wormeester, 2017a]. [1]

Another important contributing factor to mining costs, is maintenance and repair. As discussed in section 3.5.3, the time between diesel engine overhaul will likely increase, due to the decrease in fuel burn. However, the higher strain on other components (because of higher speed) will cause higher wear on these components, relative to non-trolley trucks. The components produce at a higher rate, hence they might wear out quicker. Eventually, all these factors will likely cause a shift in the hourly maintenance and repair rates per interval. Labor costs are also part of the mining costs. Changes due to the implementation of trolley assist can be a reduction in required truck operators and mechanics (when there are fewer trucks required), and more electricians for trolley line maintenance.

The NPV takes into account the time value of money, so the period-dependent variation in operating costs plays an important role in the NPV of a mine. By delaying for example the engine overhaul, the increased operating costs (M&R) related to the engine will occur later in the mine life. This could have an advantageous effect on the NPV, if compared to the earlier occurrence of engine overhaul costs for diesel only trucks. In general, it is best practice to place the trolley line on a ramp via which the most material is transported. Hence, the amount of material that will be transported via the trolley line is dependent on the production rates, and can differ per period. This also contributes to a variable operating cost. The variation in operating costs is one of the key considerations when moving the trolley line. The balance between the cost of relocating versus the gain on operating costs can differ per period, so the optimum time to move the line is highly dependent on operating costs.

The effect of trolley assist on operating costs cannot be expressed in the same way as the capital costs, since they are not absolute. Based on findings in literature, potential changes in operating costs are mostly related to savings in energy cost and savings in diesel engine overhaul costs. [2, 3, 20] Janusauskas et al. [1] reports a savings of 6% on truck operating costs at large open pit operations in Canada. Steynfaard et al. [14] reports a savings of more than 60% on hourly hauling costs at the Sishen mine in South Africa. It must be noted, that the magnitude of this reduction in hauling costs is likely due to the high difference in diesel price and electricity price at that time.

3.7. Potential Savings

Resulting from the previous sections, the most familiar benefits of trolley assist are the increase in truck speed and the decrease in fuel consumption. Since these benefits have already been discussed, this section will focus more on the effects these benefits lead to.

In general, the increase in speed (see equation 3.1) leads to a higher truck productivity. This benefit can be categorized in two scenarios: reduced truck fleet size or increased production. The goal of implementing trolley assist remains the same for both scenarios, i.e. achieve lowest cost per tonne.

3.7.1. Reduced truck fleet size

The potential savings in this scenario follow from the reduction in required amount of haul trucks. Because of the higher speed achieved with trolley, the cycle time of the haul trucks decreases. This means that per hour, and thus per day or year, a truck can complete more cycles compared to non-trolley trucks. As a result, with more cycles completed per hour, more tonnes will be transported per hour: truck productivity increases. Hence, the same annual production target of the mining operation can be achieved with fewer trucks. [1]

The purchase of large mining trucks is a significant capital expenditure. The reduction in this expenditure, due to a smaller truck fleet, therefore will have a positive effect on the NPV as a one time saving. Potentially, there will be a corresponding decrease in personnel requirements, cutting labor costs. These savings influence the operating costs, so in this scenario the benefits are expressed as both one time savings and yearly savings. [3]

It should be noted, that the potential reduction in truck fleet is highly dependent on the actual gain in cycle time that is realized. This is determined by factors such as length, availability and utilization of the trolley line, but also on operational conditions like truck bunching, the distance between haul trucks on the ramp, shovel productivity and configuration of the haul roads. With accurate strategic mine planning (and with a good understanding of the performance of the system), the savings related to this scenario pay off directly from the start of trolley implementation.

3.7.2. Increased production

As discussed in section 3.7.1, the higher speed that can be achieved with trolley assist results in a higher truck productivity. In the previous scenario, the target yearly production remained the same, reducing the truck fleet. The other scenario is to keep the same amount of trucks, increasing yearly production. This results in additional tonnes moved and potentially a higher amount of ore production, on condition that the rest of the fleet (e.g. shovels) can match the increase in productivity and the processing facility is capable of handling an increased amount of ore. [3]

The potential increased ore production has a positive influence on the NPV, as the operating costs are offset against a higher profit. Waste can be removed more rapidly, allowing access to the ore body in an earlier stage of the operation. Depending on mine economics, this might result in a shorter payback period (considering time value of money). The savings related to this scenario therefore occur throughout the mine life, rather than at the start of trolley implementation.

3.7.3. Greenhouse gas emissions

The transition of power supplied by the diesel engine to power supplied by the overhead trolley lines does not only result in productivity benefits and a decrease in fuel costs. The reduction in fuel consumption by the trucks can significantly reduce the emission of greenhouse gases (GHG). With every liter diesel fuel that is combusted, approximately 2.7 kg CO_2 is emitted. According to Janusauskas et al. [1], trolley assist could result in a 10% to 30% decrease of CO_2 emissions in large open pit mines. Additionally, NO_x and diesel particular matter (DPM) emissions could be reduced. [1]

During the last decade, there has been an increased focus on the effect of greenhouse gas emissions on climate change. With recent policies on reducing the world's carbon footprint, the mining industry faces potential radical regulations with respect to the production of CO_2. Based on current news items and publications, countries worldwide are looking at posing carbon taxes on energy intensive industries, such as the mining industry. In the past, the mining industry was exempt from energy taxes in most countries with such a tax regulation. Australia passed a law on carbon tax back in 2011, however it was repealed shortly after. South Africa is planning on implementing a carbon tax by the end of 2017 or early 2018. The government of Canada has recently proposed regulations on carbon pricing, which have been backed by the Canadian mining industry. [23–25]

Mining operations that use trolley assist, and therefore reduce their fuel consumption, will likely be less affected by these carbon tax policies than non-trolley operations. Therefore, trolley assist could have a positive impact on the environmental footprint of the operation, but also on the project economics. It has to be noted that in this thesis the different types of electricity generation have not been taken into consideration. It goes without saying that the impact of trolley assisted haul trucks on the carbon footprint is indisputably related to the origin of the electric power that is used.

Besides the environmental and potentially economic benefits of reducing GHG emissions, there is a practical side as well. During cold winters, in for example the Arctic, the amount of particulate matter (such as emitted diesel fume particles) in open pit mines is very high. Normally, the layer of air above the surface is heated up by solar radiation. This causes the air close to the surface to rise, while the cold, higher air sinks towards the surface. This convection allows particulate matter to dissipate into the air, transporting it away. In cold areas, the layer of air close to the surface cannot be heated enough to rise up, preventing this convection cycle. Effectively, without convection the air with particulate matter is trapped, causing an increasing build-up of polluted air near the surface. For mining operations, this means that during winter months the production might have to be downscaled, to reduce the amount of diesel fumes being exhausted in the trapped layer of air. Trolley assisted haul trucks can provide a solution for these operations: with less diesel fuel emissions exhausted per cycle, they could prevent the need for downscaling production during winter months. [26]

4

Strategic Mine Planning

The goal of strategic mine planning is to maximize the value from extracting and processing a mineral resource, taking into account long-term strategic objectives and operational constraints. The mine plan determines the sequence in which ore blocks should be extracted in order to maximize the Net Present Value (NPV), taking into account the time value of money. This translates into a large-scale optimization problem, which is usually referred to as the scheduling problem. The strategic mine plan is developed during the early stages of a mining project and continues to be of high importance during the entire life of the mine. It is the key determinant of amongst others production volumes, extraction rates and life of mine.

Development of a strategic mine plan requires input of economic and geotechnical data that can be considerably uncertain, such as commodity prices or ore grades. This makes the scheduling problem a very complex and dynamic optimization problem. There can be many possible solutions, linking present-day decisions to long-term outlooks. There is a range of mine planning software packages available, using various algorithms that all serve the same goal: determining the optimum yearly schedules in order to obtain the highest NPV. Most of the commercial software packages are build around the same algorithm and roughly follow the same steps in solving the scheduling problem.

4.1. Net Present Value

The Net Present Value (NPV) gives an estimation of the fundamental value of a project, indicating the level of profitability. The concept of the NPV of a project is based on the time value of money. In other words: \$1 today is worth more than \$1 tomorrow. The NPV combines periodical, discounted cash flows and initial capital investment, to determine the present value of a combination of future cash flows. See equation 4.1. [21, a]

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{4.1}$$

where:
t = number of time periods
T = final time period
C_t = net cash flow during period t
r = discount rate
C_0 = total initial investment costs

The inflow and outflow of money make up the total cash flow. In case of mining operations, the revenue of the product forms the inflow of money. Expenses like operating costs, capital costs and tax are outflows. The discount rate is a measure to calculate the present value of a dollar that will be received in period t. The discount rate is similar to the market interest rate, but is usually adjusted for financial risk as well. [21, a]

From a strategic mine planning perspective, the specific periods at which cash flows occur determine the optimum mine schedule, producing the maximum NPV for the project. The sequence of the extraction of ore blocks is the foundation for the mine schedule and eventually for the NPV. The following sections will describe the process of starting with a geological block model to determine the NPV of a project.

4.2. Block Model

The block model forms the basis for strategic mine planning. In a block model, the deposit is represented by equally sized blocks, which contain geologic information such as ore grade, tonnage and rock characteristics. This information is obtained from drill hole data, collected with drill hole measurements and subject to geostatistical analyses. In Figure 4.1, a deposit is visualized by a diagrammatic representation of a geological block model.

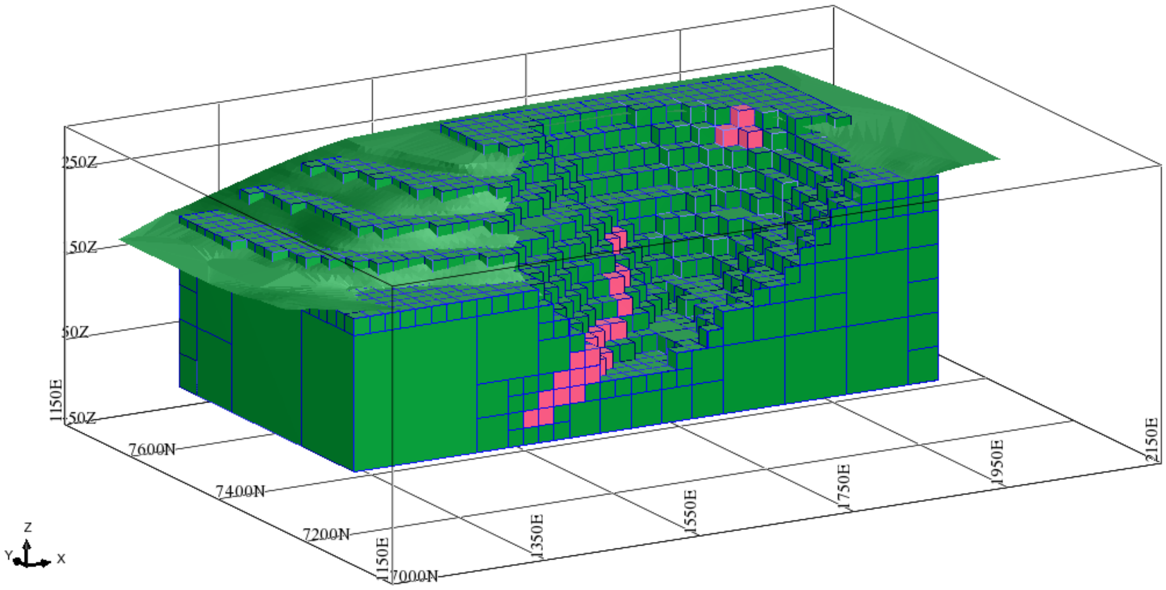


Figure 4.1: Diagrammatic view of a 3-D block matrix containing an orebody. Ore bearing blocks are indicated in red.

In order to accurately represent the deposit, as much details as possible should be included in the blocks. Theoretically, the smaller the block, the more accurate the estimation of its value will be. However, from a practical point of view, small blocks are usually not the best option. Besides highly increasing the system of equations that will need to be solved due to the higher number of blocks in the model, the error of estimation also increases with smaller blocks. Therefore, the 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. [21, b]

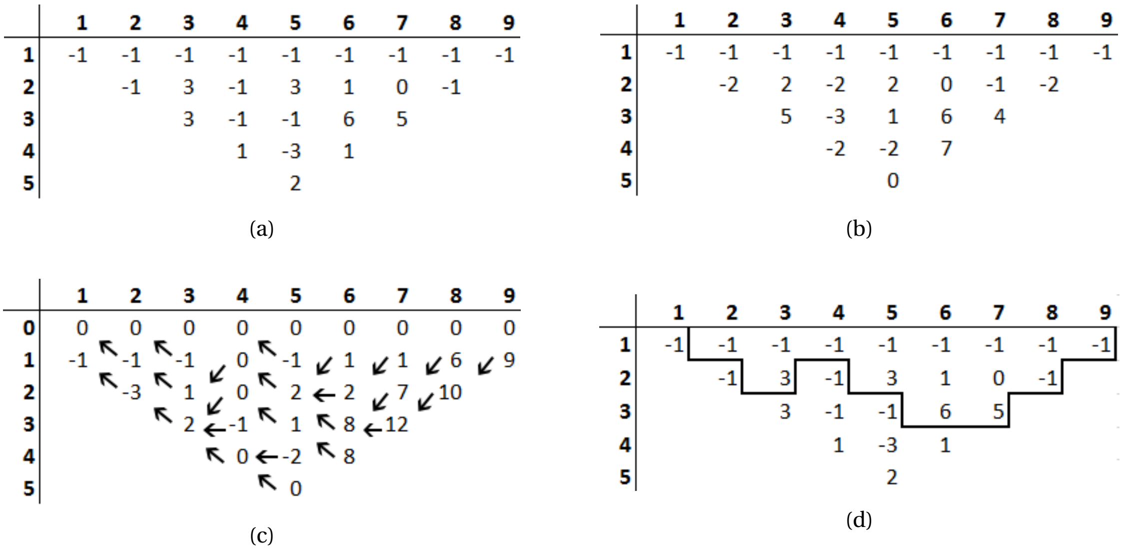
By taking into consideration economic parameters such as commodity prices, mining and processing costs, an economic block model is generated from the geologic block model. Based on the economic block values in this model, it can be decided *whether* a certain block should be mined, *when* it should be mined and *how* it should be processed after it has been mined, i.e. whether it should be sent to processing plant, stockpile or waste dump. The economic value of a block determines whether the block is categorized as waste or ore. [27]

4.3. Ultimate Pit Limit

Based on geometric, economic and production constraints, pit limits can be generated. The ultimate pit forms the boundaries within which material can economically be mined. Using the economic block model, it is analyzed whether blocks are worth mining, by means of a break-even calculation. In other words, it is calculated if the profit of the block can pay for mining of the (waste) blocks that need to be removed in order to get to the block. This is done by using the Lerchs-Grossmann (LG) algorithm, maximizing the undiscounted profit. [27]

The LG algorithm is a graph-theoretical programming algorithm, demonstrated by Helmut Lerchs and Ingo

Grossmann [28], using a two-dimensional cross section of a block model (Figure 4.2a). Taking into consideration defined slope constraints, the algorithm calculates the cumulative value of extracting a column of blocks, by summing up the values of a certain block and all blocks above it in the same column, see Figure 4.2b. Next, for each block it is analyzed if it can pay for its own extraction and processing, as well as the mining of any overlying blocks. Starting at the left outside limit of the block model and working top-down, left to right, the cumulative sum of the cross-section is calculated by selecting 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, diagonally below to the left). The left block that has been used to calculate the cumulative value, is indicated with an arrow, see Figure 4.2c. By selecting the most positive value of the upper row and tracing back the arrows from that point, the ultimate pit outline is represented, as shown in Figure 4.2d. The value of the start point is also the total value of the pit. [28, 29]



(a)

	1	2	3	4	5	6	7	8	9
1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2		-1	3	-1	3	1	0	-1	
3			3	-1	-1	6	5		
4				1	-3	1			
5					2				

(b)

	1	2	3	4	5	6	7	8	9
1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2		-2	2	-2	2	0	-1	-2	
3			5	-3	1	6	4		
4				-2	-2	7			
5					0				

(c)

	1	2	3	4	5	6	7	8	9
0	0	0	0	0	0	0	0	0	0
1	-1	-1	-1	0	-1	1	1	6	9
2		-3	1	0	2	2	7	10	
3			2	-1	1	8	12		
4				0	-2	8			
5					0				

(d)

	1	2	3	4	5	6	7	8	9
1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2		-1	3	-1	3	1	0	-1	
3			3	-1	-1	6	5		
4				1	-3	1			
5					2				

Figure 4.2: Example of the two-dimensional Lerchs-Grossmann algorithm for a block model with a slope angle of 45 degrees. From top to bottom: (a) Cross-section with the original block values. (b) Cross-section showing the column sum block values. (c) Cross-section with cumulative block values, with an additional row of zeros representing air blocks. The arrows indicate the most positive value directly to the left. (d) Cross-section with the original block values, showing the ultimate pit limit. The total value of this pit is 9.

To determine the final pit in a three-dimensional model, the results of multiple two-dimensional cross-sections throughout the model are merged. This usually does not result in a completely optimum solution, because the separate pit contours do not fit together due to mismatches with the slope constraints in 3D. Over the years, alongside the development of software technology, many algorithms that attempt to achieve a more optimum ultimate pit limit have been developed, most of them with the LG graph theory as fundamental approach. The base algorithm demonstrated by Lerchs and Grossman is considered a very practical approach to determining the ultimate pit limit. However, it requires a high computational capacity. Development and improvement of these algorithms still plays an important role in todays mining industry. [28, 29]

4.4. Pit Geometry

Geometric parameters can impose important constraints for the design and planning of an open pit mine. Therefore, taking into account geometrical considerations during the mine planning process is fundamental for every mining project.

One of the most influencing geometric parameters is the slope angle. An optimum slope angle ensures the stability conditions of the pit walls whilst minimizing the stripping ratio. Hence, it has a considerable impact on the project economics. The slope angle is dependent on the rock characteristics and is influenced by the bench geometry and ramp width.

Bench geometry is defined by parameters such as height, width and face angle. The bench height is fundamental to the rest of the bench dimensions and is usually dependent on the size of the mine and the range of the loading equipment. Benches are horizontal sets of blocks and therefore the bench dimensions are always in accordance with block dimensions. The bench width will mainly depend on the bench height and purpose (bench type). Besides its dependency on the local rock characteristics, the face angle of a bench can be influenced by various circumstances such as face orientation and blasting practices. [21, c]

The width of the ramp depends on the haul road geometrics, which are defined by the type of equipment, the number of lanes and berm requirements. The haul road width is always determined based on the width of the largest vehicle. Typical rules of thumb for minimum haul road width are listed in Table 4.1. These rules of thumb are proposed for straight roads, with a regular grade. [30] In practice, mines tend to go for half a truck width wider than the proposed width factor in Table 4.1. As discussed in 3.5.2, the installation of the wayside system for trolley assist requires additional width of the haul roads (see Figure 3.3).

Table 4.1: Minimum haul road width for conventional open pit mining operations. The width factor has to be multiplied with the largest vehicle width, in order to determine the minimum haul road width. Source: Atkinson [30]

Number of Lanes	**Width Factor**
1	2.0
2	3.5
3	5.0
4	6.5

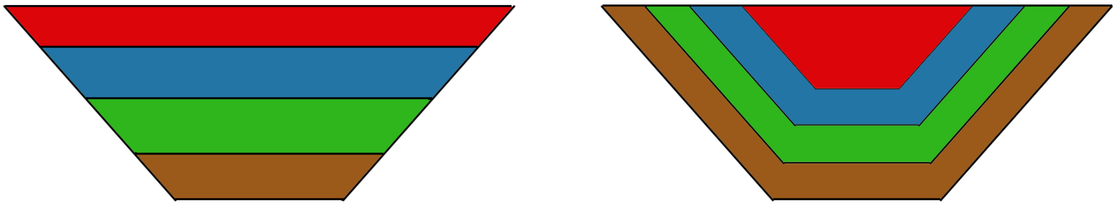
4.5. Sequencing & Pushback Generation

For planning purposes, more manageable units are defined within the ultimate pit limit. By creating pushbacks, the deposit is divided into so called nested pits or phases, based on the the optimal order of removal of the blocks. This is referred to as sequencing. [27]

The purpose of sequencing is to form a basis for the scheduling process. Nested pits are generated by varying cost and profit parameters, and are based on undiscounted block values. Each alteration in the parameters will result in a different optimum pit limit within the generated pit shells. This process is also referred to as pit parameterization. The sequence is the order in which the nested pits should be mined, which is adhered to as much as possible when generating pushbacks. [21, d]

Important pushback design criteria are also related to pit geometrics, e.g. the bench width (operating benches and inactive benches), the operating slope, the haul road width and grade, the bench height and the ultimate pit limit. Because of the importance of haul road design when generating pushbacks, this phase is critical when implementing trolley assist. [21, e]

Most mine planning software packages propose a best and worst case sequence, based on the amount of waste that has to be stripped per pushback to extract the ore. Figure 4.3 shows a schematic interpretation of the worst and best case. In the worst case scenario, each bench is mined sequentially until the final pit is reached. Mining is started at the top bench and progress straight downwards, producing the lowest NPV. In the best case scenario, the nested pits rather than benches are mined sequentially. Mining is started at the pit with the highest value, progressing towards the pit with the lowest value. This scenario will produce the highest NPV. Usually, neither the best nor worst case scenario is a realistic approach, so the specified case will be somewhere in between (with the aim of being as close to the best case as possible). Therefore, pushbacks are typically designed to be increasing in size but decreasing in average value per ton. The process of mining from the smallest pit to the largest (ultimate) pit is called pushback mining. [27]



(a) (b)

Figure 4.3: Schematic representation of (a) the worst case mining sequence and (b) the best case mining sequence.

4.6. Scheduling

Scheduling is the process of determining which parts of the pushbacks are mined in which period, with the aim of maximizing the NPV, thus taking into account discounted block values. The important difference with sequencing is that during scheduling a specific time for removal of a mining block is appointed, rather than only the order of removal. As discussed in the previous section, pushbacks are selected as increasing in size but decreasing in value per tonne. To appoint the time of extraction to a specific part of the pushback, it is subdivided into incremental units: bench-phases. From an optimized NPV perspective it is most profitable to mine the smallest pit with the most high value ore first. Pushbacks are mined block by block, top-down and can take multiple years to be fully extracted. To achieve an optimal NPV, multiple pushbacks can be mined simultaneously (thus benches on different levels) to balance the amount of waste and ore that is mined.[27]

The schedule is dependent on parameters such as mining and processing capacity. From a long-term planning perspective, the objective of mine planning is to achieve the overall production targets and to maximize life of mine. Short-term planning focuses on the day-to-day operation, meeting specific production targets and minimize cost per tonne. The long-term and short-term mine plan combined form the strategic mine plan. [31]

4.7. Short-Term Planning

The step-by-step strategic mine planning process as described in the previous sections focuses on achieving a maximum NPV in the long term, emphasizing the long-term performance of a mining operation. Besides the long-term planning, short-term scheduling should also be considered an important part of mine planning. Short-term scheduling is about the day-to-day performance of the operation, and concerns time spans less than one year. Smooth and efficient use of equipment is one of the key contributers to an adequate short-term schedule. The purpose of short-term scheduling is to meet daily production targets, minimizing the therewith associated costs. Basically, the short-term mine plan should be a subsidy towards meeting the long-term objectives as defined in the strategic mine planning process, making the long-term plans operationally feasible. Usually, during the short-term planning process there is more detailed and accurate information regarding the ore body than the long-term planning. [32]

5

Case Study

To assess the impact of trolley assisted haul trucks on strategic mine planning in open pit mines, a case study was executed. The following chapter contains a step-by-step breakdown of the work that was done, as well as the presentation and interpretation of the results that were obtained.

5.1. Objective

The purpose of the case study is to assess the economic difference between relocating the line in an early stage of a pushback, versus moving it in a later stage. Repositioning the overhead lines will cost money and time, but operating on trolley assist on the most productive haul route will impose the highest savings on operating costs. Therefore, two trolley assist scenarios will be assessed, each with the relocation taking place in a different period of time. By means of an NPV analysis, the preferable option will be appointed. Although the work done for this project is specifically focused on the case study, the step-by-step breakdown could serve as a guidance for other projects as well.

In addition, the case study will provide an NPV comparison between a diesel only application and the trolley assist system. For the purpose of this study, it is assumed that the truck fleet only consists of Cat 795F AC haul trucks. It is assumed that the trucks are loaded by Cat 7495 electric rope shovels.

The software used to execute the case study are GEOVIA GEMS, GEOVIA Surpac, GEOVIA Whittle, Caterpillar Fleet Production and Cost (FPC) and Microsoft Excel.

5.2. Case Description

For this thesis, a theoretical case named Ghana Gold was provided. Before discussing the work that was done for the project, the case will be briefly introduced. It is important to note that the case study assumes an active operation, and the assessment of trolley assist commences from the intermediate pit design as starting point.

5.2.1. Deposit

The Ghana Gold case concerns a typical Ghanaian Archean gold deposit, with the main zone of mineralization located in between the Birimian Supergroup and the overlying Tarkwaian Group. Gold mineralization occurs in moderately dipping quartz veins, which are predominantly located in shear zones within sedimentary rocks from the Birimian Supergroup. [33] The tabular orebody (see Figure 5.1) extends approximately 850 meter East-West and 1,475 meter North-South, dipping East with 28 degrees and reaching a maximum depth of 410 meter below the surface.

5.2.2. Block Model

The block characteristics are given in Table 5.1. The density of waste blocks is 2.9 t/m^3 and the density of ore blocks is 2.74 t/m^3. The gold grades are reported in grams per tonne. The grades range from 0.051 g/tonne to 7.304 g/tonne, with an average of 2.042 g/tonne. The original model distinguished three types of rock, being oxide, transitional and fresh rock. Four rock zones were identified, being the foot wall zone, main crush zone,

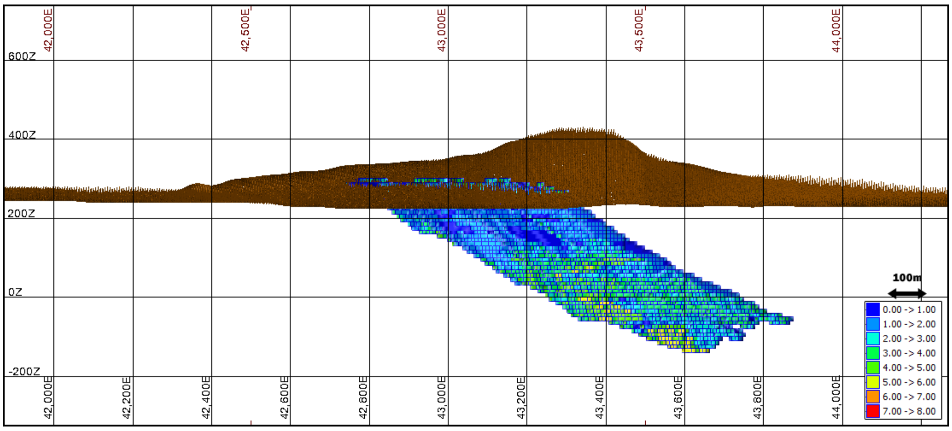


Figure 5.1: Section view (West-East) of the Ghana Gold deposit and topography.

Table 5.1: Ghana Gold block model characteristics.

	X	Y	Z
Block dimension	10	25	10
Block model size	145	91	65
Block model origin	43,000	46,800	450

hanging wall zone and the waste zone. Together, this resulted in twelve different rock codes. As each rock code had its own characteristics, this made the model very complex. Therefore, it was decided that for this project, all rock codes are treated equally in terms of rock characteristics.

5.2.3. Pit Design, Infrastructure & Production

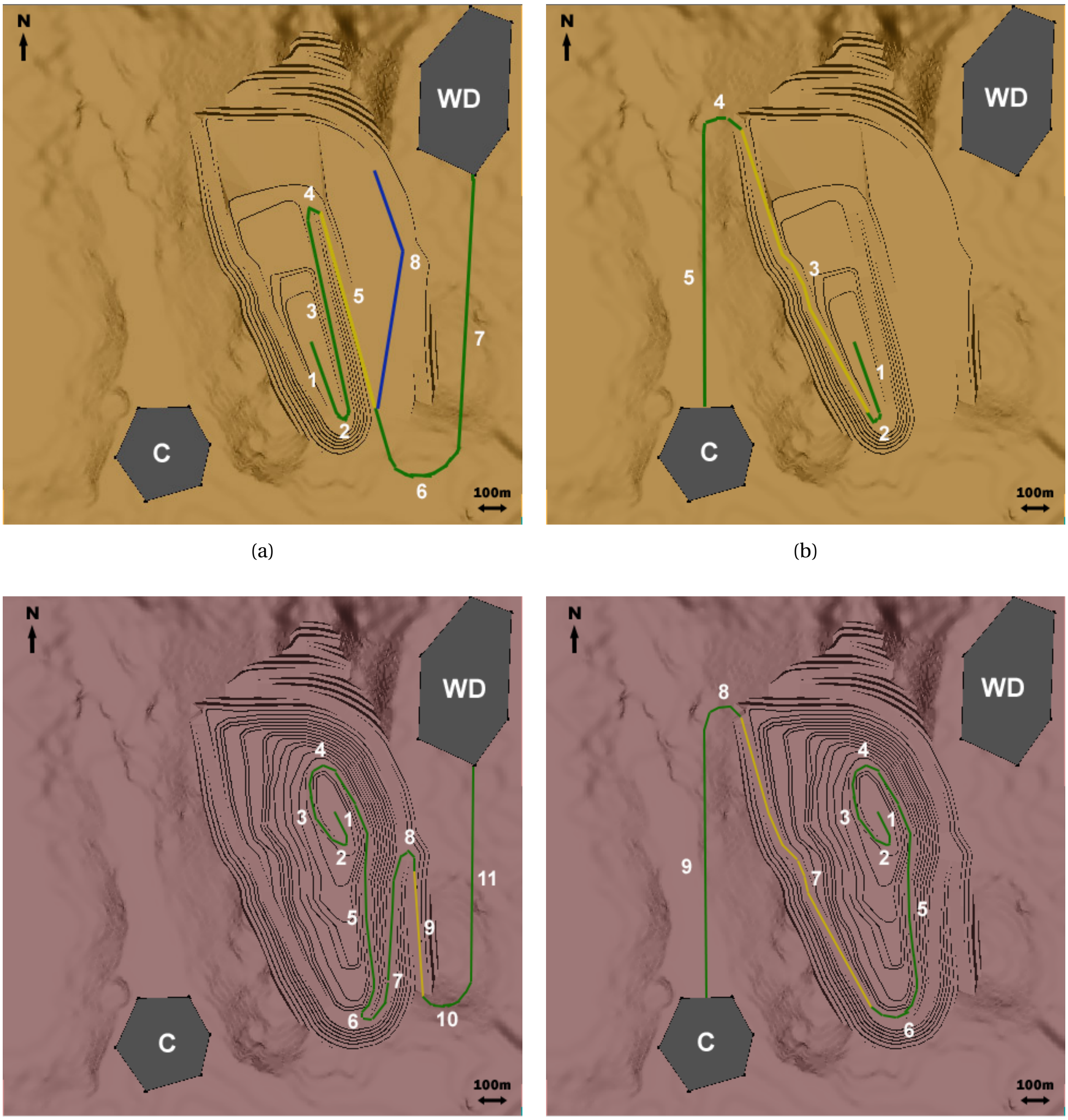
Two pits have been created for this thesis: an intermediate pit and a final pit. The pit designs are presented in Figure 5.2. The location of the waste dump (North-East) and the crusher (South-West) are also shown. The bench height is 20 meter, with a bench face angle of 70 degrees, and the ramp width is 60 meter with an inter-ramp angle of 55 degrees. This results in an overall slope angle of 45 degrees. To reach the intermediate pit, 15.7 Mt of material has already been extracted. The intermediate pit is approximately 900 meter wide, 1900 meter long and 180 meter deep.

Since the waste dump and crusher are located on opposite sides of the pit, different haul routes for ore and waste are used, with exits on the North-West side and South-East side of the pit. The haul routes for the intermediate pit are shown in Figure 5.2. Yellow lines indicate the trolley segments, which are installed both on the foot wall and hanging wall side. In section 5.3.3, the haul profiles will be discussed in more detail.

5.3. Cost Model

The cost model forms a foundation for cost inputs in GEMS and Whittle and is an important part of the dynamic, iterative strategic mine planning process. The model contains the conventional estimates for operating and capital costs, but provides the opportunity to include factors related to trolley assist, e.g. regarding productivity and fuel costs. These are set up in such a way that a comparison between diesel only and trolley assist can easily be made. In the cost model, one period corresponds to six months.

Project costs are heavily dependent on project specific characteristics, such as location, commodity and operating conditions. There is very little cost data available for mining operations in non-Western countries and cost data related to trolley assist operations is also limited. Therefore, it needs to be taken into account that the cost model generated for this project mostly contains estimated values based on cost data from other operations and estimates provided by Caterpillar experts. To correct for uncertainty of these estimations, Monte Carlo simulations have been used. After discussing the Monte Carlo approach to cost estimation, the structure of the cost model will be discussed. Important input parameters will be given and justified. A



(a) (b)

(c) (d)

Figure 5.2: Pit designs for the Ghana Gold case, with haul routes for (a) pit floor and upper working bench to the waste dump (WD), in the intermediate pit, (b) pit floor to crusher (C), in the intermediate pit, (c) pit floor to waste dump, in the final pit and (d) pit floor to crusher, in the final pit. The numbers represent the haul segments. The yellow line indicates a potential trolley assist segment.

detailed overview of the cost model can be found in Appendix A.

5.3.1. Monte Carlo Simulation

The Monte Carlo Simulation process uses random numbers to approach the expected value of a variable, in this case costs. By repeating this random number method a large number of times for the same cost estimate, different values will be generated. The average of this value distribution is an approach to the expected cost based on a certain estimation range.

The costs are estimated in three ways: a minimum value, a maximum value and a most likely value. Dependent on the type of cost, these estimations are based on values found in literature or obtained from Caterpillar experts. Based on minimum, maximum and most likely cost estimations, the Monte Carlo simulation uses a triangular distribution to determine the expected cost. According to Lampe and Platten [34] the triangular distribution is a suitable distribution for cost estimation, since it is a near approximation of the lognormal distribution, but simpler to use. The lognormal distribution is often used for cost estimation and the difference in outcome of the Monte Carlo simulation compared to the triangular distribution is insignificant. The basic trigonometry of the triangular distribution is shown in the probability density function in Figure 5.3, where:

- A is the minimum cost estimate
- B is the maximum cost estimate
- C is the most likely cost estimate
- y' is the probability of cost estimate C
- x' is the simulated cost estimate
- r' is the probability of x'

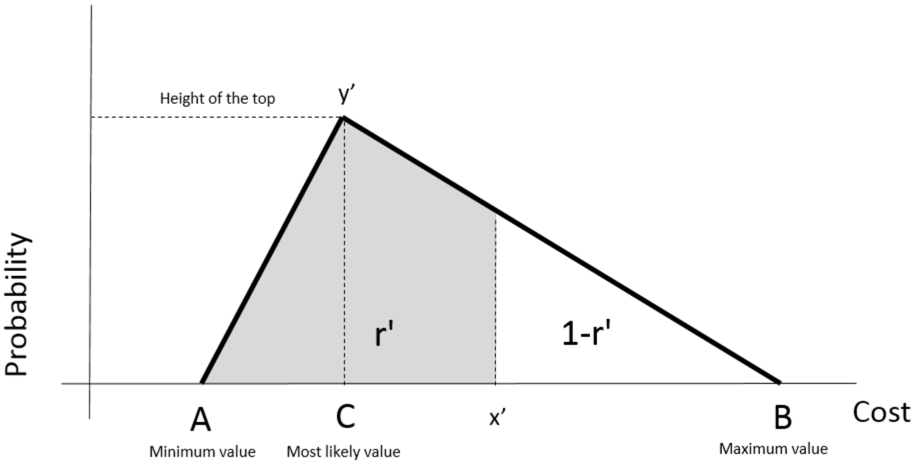


Figure 5.3: Probability density function of a triangular distribution.

As the total area under the probability density function should be equal to 1, the height of the top y' is defined as follows:

$$area = \frac{1}{2} * base * height = 1$$

$$= \frac{1}{2} * (B - A) * y' = 1 \tag{5.1}$$

$$y' = \frac{2}{B - A} \tag{5.2}$$

For the Monte Carlo simulation, a random number r' between 0 and 1 has to be generated, which is used to determine the simulated cost estimate x'. The random number r' is the probability that the actual cost is less than simulated cost estimate x'. The probability that the actual cost is greater than x', is (1-r').

The equation to calculate the value of x' is dependent on whether r' is on the left or on the right side of C. This can be tested by comparing the value of r' to the area of the triangle ACy' (also referred to as the "mode", see equation 5.3), and using the appropriate equation to calculate x', as shown in equations 5.4 and 5.5.

$$\begin{aligned}
area \quad ACy' &= \frac{1}{2} * base * height \\
&= \frac{1}{2} * (C-A) * \frac{2}{B-A} \\
&= \frac{C-A}{B-A}
\end{aligned} \tag{5.3}$$

$$If \quad r' \leq \frac{C-A}{B-A}, \quad then \quad x' = A + \sqrt{r'(B-A)(C-A)} \tag{5.4}$$

$$If \quad r' \geq \frac{C-A}{B-A}, \quad then \quad x' = B - \sqrt{(1-r')(B-A)(B-C)} \tag{5.5}$$

The simulation of cost estimate x' is repeated 1000 times (with 1000 random numbers). The average of x' is assumed to be the expected cost.[34] The Monte Carlo simulations of cost estimates have been performed in Microsoft Excel 2016.

5.3.2. Shift Roster

The goal of a mining operation is to operate as many hours per year as possible, to achieve maximum yearly production and quickest return on capital investment. However, the total scheduled hours do not equal the total available hours per year.

First of all, typically a mine cannot operate 365 days a year due to, for example, holidays or seasonal restraints. The available days per year are divided into shifts, for this case study two 12-hours shifts a day are assumed. Per shift, there will be lost time due to shift change, breaks and refueling. Additionally, daily delays due to e.g. blasting have to be considered. This results in a total amount of lost hours per year. By subtracting the lost hours from the total available hours, the scheduled truck hours are defined.

In the cost model, years are split up into periods of six months. Up to this point, there is no difference in diesel only operation or trolley assist operation. The following inputs have been used:

- Days of operation: 360 days per year
- Hours per shift: 12 hours
- Shifts per day: 2
- Lost time:
    - Shift change: 0.5 hour per shift
    - Breaks: 0.75 hour per shift
    - Refueling: 1 hour per day
    - Blasting delay: 1 hour per day
    - Other delays: 1 hour per day

As a result of the shift roster calculations, there are 6,840 scheduled hours per year, corresponding to 3,420 scheduled hours per period. Based on available total hours of 8,640 hours per year (for 360 days), this results in a scheduled utilization of 79%.

5.3.3. Haul Profiles

Haul profiles give the distance over which material has to be transported to reach its destination. Based on the distance traveled, the grade of the haul road and the speed of the haul truck, the total cycle time can be calculated. Usually, there are many different haul profiles possible in a mine, since material will be excavated on multiple active benches. This highly influences average cycle times of the haul trucks. To maintain a manageable approach to the project, the haul profiles have been simplified for this case study.

Only one haul profile for ore haulage is assumed in the intermediate pit and final pit, going from the pit floor to the crusher. These haul profiles are referred to as IP_C and FP_C. Since the haulage of ore occurs on the foot wall side of the pit, the ramps for ore haulage in the intermediate pit are permanent. For waste haulage in the intermediate pit, two haul profiles are assumed. The first one goes from the upper working bench to the waste dump (IP_WD_upper) and the second goes from the pit floor to the waste dump (IP_WD_lower). By the end of the pushback, these two haul profiles are combined into a new profile: IP_WD_reloc. In the final pit, there also is only one haul profile for waste: from the pit floor to the waste dump (FP_WD).

The haul profiles are displayed in Figure 5.2 on page 27. A yellow segment indicates a potential trolley line. The distances of the haul profiles are measured in GEMS. The results are shown in Table 5.2, in which the numbers of the segments correspond to the segments in Figure 5.2.

Table 5.2: Distances of the different haul profiles in meters.

Segment	IP_WD_upper	IP_WD_lower	IP_WD_reloc	IP_C	FP_WD	FP_C
1	1,350	290	290	290	130	130
2	380	80	80	80	60	60
3	1,150	890	1,250	1,700	250	250
4		80	80	140	250	250
5		1,000	1,650	1,200	950	950
6		380	230		140	1,400
7		1,150	1,150		600	300
8					80	140
9					600	1,200
10					230	
11					1,150	
Total (m)	2,880	3,870	4,730	3,410	4,440	4,680

Cycle times and fuel rates are determined with Caterpillar Fleet Production and Cost (FPC). Besides the haul profile distances, FPC requires specification of the equipment. The type of truck (Cat 795F AC) can be selected, with fuel data related to this type of truck already incorporated in the program. Because of the weight of the trolley package, the empty weight of a trolley truck is higher than that of a conventional truck. For haulage, this imposes no difference in speed and fuel burn. However, for the empty return of the truck, a trolley truck will burn more fuel uphill or on a flat. Hence, to obtain the production data for trolley assist, the empty truck weight is adjusted in FPC.

To let FPC calculate the cycle times, a loader must be selected. For the Ghana Gold case, the Cat 7495 electric rope shovel is used. The bucket capacity is assumed to be 45 cubic meters, with a fill factor of 90%. This means that four passes are required to load the haul truck, with the first pass being 0.1 minutes and the next three 0.63 minutes per pass. This results in a total haul time of 1.99 minutes per truck. Further assessment and optimization of the loader is out of scope of this thesis, since only the load time is required for determination of the cycle times.

For the trolley line segments, the potential speed of the truck has been adjusted according to equation 3.1. The ramp grade is 10% and the rolling resistance is 2%. Hence, the speed on trolley is 22 km/h. An acceleration of 2 m/s^2 is assumed under the line, which is used for calculation of the time on the trolley ramp. The fuel burn under trolley is based on the time spent under the line, assuming that during this time the diesel engine idles along. The fuel rate when idling is assumed to be 60.6 L/h.

Detailed results from the haul profile calculations can be found in Appendix A.

5.3.4. Ore and Waste Production

At this point, ore and waste movement is kept separate, in order to adequately calculate productivity requirements based on their specific haul profiles. In order to assess the impact that the choice of trolley relocation period has on the schedule and NPV, two scenarios have been generated. Figure 5.4 shows the trolley line relocation, relative to the initial haul profile of the intermediate pit to the waste dump.

Scenario 1

- Period 1 denotes the period in which the operations in the intermediate pit start.
  - Haul profiles: IP_WD_upper, IP_WD_lower, IP_C.
- Period 4 denotes the period in which the trolley line is relocated.
  - Haul profiles: IP_WD_reloc, IP_C.

Scenario 2

- Period 1 denotes the period in which the operation in the intermediate pit start.
  - Haul profiles: IP_WD_upper, IP_WD_lower, IP_C.
- Period 5 denotes the period in which the trolley line is relocated.
  - Haul profiles: IP_WD_reloc, IP_C.

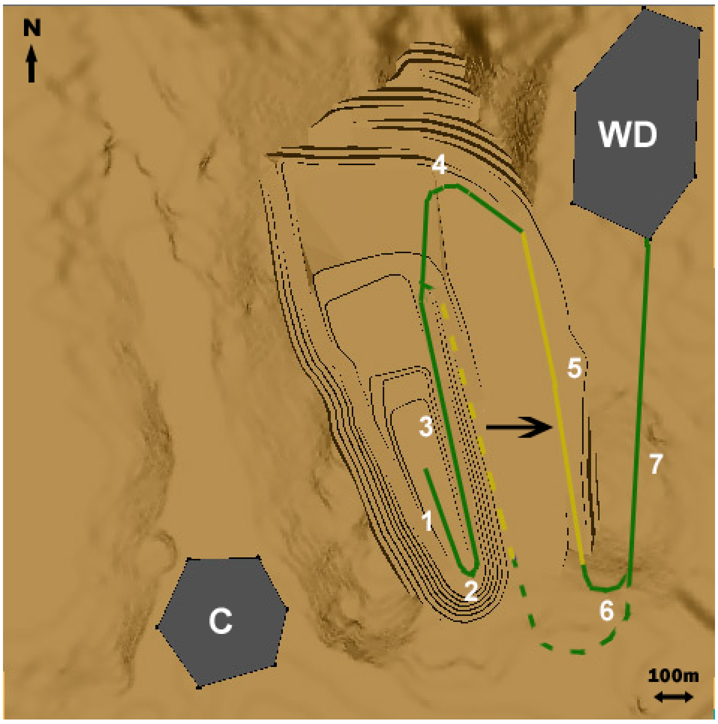


Figure 5.4: Plan view of the intermediate pit, with the waste dump haul route before (dashed line, as presented in Figure 5.2a) and after relocation.

Scenario 1 follows the natural progress of the unconstrained mine design, with relocation of the trolley line occurring in period 4, as the ramp advances towards the outer side of the pit. In Scenario 2, the relocation of the trolley line is delayed by one period. This will suspend the costs of moving the line, but it will also pose a constraint on mine planning, since the ramp must stay in place during period 4. During the scheduling phase, it will be assessed what the impact of the relocation on material movement is.

The ore and waste production rates are based on the initial Whittle schedule, that was used for the design of the intermediate and final pit. In the periods before relocating the trolley line, the assumed waste production is 20 Mtpa and the assumed ore production is 4 Mtpa. After relocation, the assumed waste production in increased to 30 Mtpa. Relocation of the line is assumed to take 4 weeks [pers. comm., Ruth, 2017b], which is roughly 17% of the period time. Therefore, during the period of relocation, downtime is accounted for in the cost model by adjusting the trolley line availability to 83% of the initial assumed value, which results in a new availability of 79%.

The production rates are used to calculate the operating and capital costs in the cost model. For each period, calculations are performed for three configurations: diesel only, trolley trucks using the trolley line and trolley trucks off the trolley line. Based on utilization and availability factors of the trolley line, the latter two are combined into a single trolley configuration later in the process. Electrical efficiency of the transformer and trolley line indicates the amount of electricity that is actually consumed by the truck, to deliver the required performance, relative to the power that is drawn from the utility grid when a truck engages to the line.

General inputs for both ore and waste are the following:

- Gross vehicle weight Cat 795F AC: 575 t
- Payload non-trolley truck: 327 t
- Payload trolley truck: 321.3 t
- Wheel motor power: 4,200 kW
- Fuel rate idling: 60.6 L/h
- Fuel rate manoeuvring: 125 L/h
- Electrical efficiency of the transformer: 95%
- Electrical efficiency of the trolley line: 85%
- 4-pass load with Cat 7495 electric rope shovel
- Load time: 1.99 minutes
- Hauler exchange time: 0.7 minutes

Dump and manoeuver time differs for ore and waste, related to the crusher and waste dump characteristics. For ore, the dump and manoeuver time is 2 minutes, for waste this is 1.2 minutes.

Based on the scenarios and periods, total cycle times are defined using the haul profiles. Theoretical productivity is calculated as the amount of cycles possible in one hour, multiplied by the payload of the truck. This productivity is theoretical, because it does not yet take into account the availability and utilization of the truck. Taking into account the theoretical productivity and the total period production target, the required truck hours are calculated. Later in the process, these hours will be adjusted for availability and utilization.

For each cycle, the fuel consumption is determined. The total fuel consumption is a combination of the fuel burn resulting from the haul profiles and the additional fuel burn from manoeuvring, loading and dumping. Additionally, dependent on the time spent on the trolley line, the electrical efficiency and the power required by the wheel motors, the electricity consumption per cycle is determined. Detailed results and calculations can be found in Appendix A.

5.3.5. Fleet

The fleet calculation combines the results from ore and waste production, to give a combined required number of trucks. This means that it is assumed that all trucks are interchangeably working on the ore and waste side, on all possible haul routes.

The required number of trucks is calculated by dividing the production target by truck productivity. This is done for ore and waste separately. In case the result of this calculation is fractional, it will be rounded up towards an integer. The required trucks for ore and waste are then summed up, resulting in a total number of required trucks.

Truck productivity is defined as the amount of tonnes a truck can transport from point A to point B, within one hour. This is broken down into the amount of cycles a truck can complete in one hour, multiplied by the payload of the truck. For trolley assist, it is important to address the availability and utilization of the trolley line at this stage, as it highly influences the average cycle times. In addition, the utilization of the trolley line is key in decreasing the fuel consumption of the trucks. For this case study, a trolley line availability of 95% and a trolley line utilization of 85% are assumed, from performance at Kansanshi [pers. comm., Mishra, 2017a].

Truck productivity also takes into account truck utilization and availability. For the Ghana Gold case study, a utilization of 79% is used (as calculated from the Shift Roster) and an overall availability of 90% is assumed. A very important note is that the cost model does not use the calculated number of trucks in further calculations. This is because the number of required trucks that is calculated, is the minimum amount of trucks is to meet the production goals, adhering to the exact availability and utilization rates. Therefore, to account for deviating truck availability, the user of the cost model is required to manually enter the decided amount of trucks. This number of trucks is used for further cost model calculations. Of course, the manually estimated number of trucks should be based on the minimum required number and is usually two or three trucks higher than the calculation.

From a productivity perspective, the maturity of the truck influences the mechanical availability and thus the productivity of the truck. Typically, a truck fleet does not consist of trucks of the same maturity, because trucks are procured in batches according the the yearly production target of the mine. This results in a complex approach towards overall fleet productivity, and hours of operation per truck. For this specific case study it has been chosen to approach all trucks with the same availability (90%). The difference the maturity of a truck brings along will be assessed in section 5.3.6, using maturity dependent maintenance and repair rates.

In summary, the following inputs for the fleet calculation have been used:

- Truck availability: 90%
- Truck utilization: 79%
- Trolley line availability: 95% (79% for the period of relocation)
- Trolley line utilization: 85%

Based on the fleet calculation, both the diesel only and trolley assist configuration start with 8 trucks. During the period that the trolley line must be relocated, 3 more trucks are required for the diesel configuration, followed by another 2 in the period thereafter. For trolley assist, only 3 new trucks are required in the period of the relocation. Detailed results and calculations can be found in Appendix A.

5.3.6. Maintenance and Repair

The impact of maintenance and repair on operating costs is represented by the average hourly rate of the truck fleet. This hourly rate is also referred to as the "M&R rate". The M&R rates are defined per maintenance interval. A maintenance interval is based on the life of the machine, expressed in hours.

Component overhauls are also included in the M&R rate. Therefore, the M&R rate of trolley trucks differs from the rate of non-trolley trucks. Components such as the engine will experience longer life and will allow an overhaul to take place later in the truck life. Other trolley components, such as the brushes on the pantograph, are an additional cost to the M&R rate.

Taking into account the unit truck hours and the expected engine overhauls, determined by the fuel consumption, an approximate increase in engine life of 42% is calculated for trolley assist compared to diesel only. This percentage is evident from the average number of hours before the first engine overhaul for diesel and trolley. In the maintenance and repair overview for the 795F AC, provided by Caterpillar, the costs related to the engine overhaul are delayed accordingly. For the additional costs related to the brushes, it is assumed that the life time of the four brushes is 2,000 hours and the replacement costs are $800 per brush.

Based on the maintenance and repair costs from Caterpillar and the above discussed modifications for trolley assist (engine overhaul and brushes), the hourly M&R rates used for this case study are listed in Table 5.3, assuming a truck life of 74,999 hours and a labor rate of 35$/h.

Table 5.3: Hourly maintenance and repair rates for Cat 795F AC trucks with and without trolley assist, in $/h.

Interval	**Start (h)**	**End (h)**	**Hourly M&R rate ($/h)**	
			Diesel Only	**Trolley Assist**
1	1	7,499	17.00	19.00
2	7,500	14,999	35.00	37.00
3	15,000	22,499	144.00	107.00
4	22,500	29,999	65.00	106.00
5	30,000	37,499	94.00	55.00
6	37,500	44,999	108.00	110.00
7	45,000	52,499	74.00	115.00
8	52,500	59,999	157.00	117.00
9	60,000	67,499	41.00	42.00
10	67,500	74,999	79.00	39.00

In addition to the hourly M&R rate, the annual cost of trolley line maintenance is assumed to be $25,000 per kilometer. The total maintenance cost is determined by calculating the average M&R rate of the mixed fleet, according to the amount of trucks that are in the various possible M&R intervals. With this average rate, the number of trucks, the average unit hours per truck and the trolley line maintenance costs, the total M&R rate is determined. Before the first overhaul for the diesel only configuration and before the addition of any extra trucks, the maintenance and repair costs for the trolley assist scenario are 12% higher than for the diesel scenario. After the addition of trucks in the period of the trolley line relocation, this difference decreases to 4%.

5.3.7. Operating Costs

The operating costs are defined as cost per tonne, and are a sum of mining costs, milling costs, selling costs and general and administration (G&A) costs. Mining and G&A costs are calculated as a function of total material moved (ore and waste), whereas milling and selling costs are only a function of ore tonnes. Selling costs are defined as royalties plus refining costs, see section 5.6.2.

The operating costs are based on reported costs from similar mining operations and expert estimates. A Monte Carlo cost analysis has been performed to simulate the operating cost items. The selected similar mining operations are located in the Ashanti belt or the Sefwi-Bibiani belt in Ghana:

- Ahafo (Newmont Mining Corp.)
- Akyem (Newmont Mining Corp.)
- Bogoso-Prestea (Golden Star Resources Ltd.)
- Tarkwa (Gold Fields Ltd.)
- Damang (Gold Fields Ltd.)
- Iduapriem (AngloGold Ashanti Ltd.)

Table 5.4 lists the minimum, maximum, most likely costs as retrieved from SNL Metals and Mining [35], and the result of the Monte Carlo simulation. A detailed overview of the costs per operation can be found in Appendix B. The costs of Iduapriem have been assumed to be the most likely costs, because of the comparable size of the operation.

Given these cost estimates, the total mining cost is $2.03/tonne. Since the cost model will calculate the energy costs, based on fuel burn and electricity use, the total mining cost has to be adjusted for truck energy costs. It is assumed that 55% of the Mine - Fuel costs is consumed by haul trucks. By subtracting this from the total mining cost, the basic mining cost for the cost model is obtained. The new fuel cost will consist of the diesel fuel and electricity consumed by haul trucks. For this calculation, a diesel price of $1.00/L and an electricity price of $0.17/kWh have been assumed [pers. comm., Wormeester, 2017a].

Table 5.4: Monte Carlo inputs and results for operating costs.

Cost Item	Unit	Minimum	Maximum	Most Likely	MC result
Mine - Labor	$/tonne	0.71	1.81	0.71	1.09
Mine - Fuel	$/tonne	0.32	1.16	0.53	0.67
Mine - Electricity	$/tonne	0.02	0.29	0.05	0.12
G&A	$/tonne	0.46	4.53	1.50	2.20
Milling	$/tonne ore	11.81	20.13	20.13	17.31
Refining	$/oz	3.00	5.50	3.00	3.82

In addition to the energy costs, the M&R costs from section 5.3.6 are used for the calculation of the mining costs. The costs are calculated as total amounts. This number is divided by the amount of material mined per period, to define the cost per tonne. The results from the calculation of operating costs are discussed in section 5.3.9. In summary, the following inputs have been assumed:

- Diesel fuel cost: 1.00 $/L
- Electricity cost: 0.17 $/kWh
- Basic mining cost: 1.51 $/t
- G&A cost: 2.20 $/t
- Milling cost: 17.31 $/t ore
- Refining cost: 3.82 $/oz
- M&R costs: interval dependent (listed in Table 5.3)

5.3.8. Capital Costs

The capital costs are usually defined as a lump sum. However, since trolley related capital costs are dependent on the length of the trolley line segment, they are given as function of distance. Typical capital expenditures for trolley assist are the trolley line, the truck trolley package and the substation(s).

For this case study, the costs made for the trolley line and substation are divided in costs for the material (hardware) and labor costs. This differentiation is due to the fact that when moving the line, the labor costs will occur again, whereas most of the material will be re-used. The labor costs for initial installation are based on a period of six weeks, with approximately 500 man hours per week against a $35/hour field labor rate. The labor costs for relocation are based on a period of four weeks. The hardware costs for trolley line relocation are estimated to be 2% of the original material costs, as new mast foundations will have to be made.

Because the Ghana Gold case concerns an active operation, two truck configurations have been assessed for trolley assist. The first configuration involves the purchase of complete new trolley trucks. For the second configuration, it is assumed that the trucks that are already used in the mine, are capable for a retrofit trolley package. This will reduce the capital investment required for the truck purchase. The retrofit packages will only be installed on the first batch of trucks, for trucks that are required later on in the life of mine, new trucks will have to be purchased.

Table 5.5 lists the minimum and maximum costs (retrieved from Janusauskas et al. [1], Brodkorb [20]), the most likely costs [pers. comm., Ruth, 2017c] and the result of the Monte Carlo simulation. The capital cost data obtained from literature holds estimates for Canada and Sweden. Since these countries impose different economic environments from Ghana, the estimates from Ruth [pers. comm., Ruth, 2017c], based on the Kansanshi mine in Zambia, are assumed to be most likely for the Ghana Gold case.

Table 5.5: Monte Carlo inputs and results for capital costs.

Cost Item	Unit	Minimum	Maximum	Most Likely	MC result
Trolley line, hardware	$M/km	1.10	2.20	1.90	1.70
DC substation	$K/unit	640	850	700	730

The results from the calculation of capital costs are discussed in section 5.3.9. In summary, the following inputs for the calculation of the capital costs have been used.

- Trolley line installation, hardware: 1.7 $M/km
- Trolley line installation, labor: 105 $K/km
- Trolley line relocation, hardware: 35 $K/km
- Trolley line relocation, labor: 70 $K/km
- New 795F AC trolley truck: 5.11 $M/truck
- Retrofit 795F AC trolley package: 310 $K/truck
- Requirement of 1 DC substation per 750 meter of trolley line
- DC substation: 730 $K/unit

5.3.9. Outputs

Using the inputs discussed in sections 5.3.2 to 5.3.8, the total operating and capital costs per period are calculated. The key costs resulting from the cost model are presented in Table 5.6 on page 37. The costs are calculated as total cost per period, and are then divided by the expected production rate to obtain costs per tonne. A complete overview of the cost model results can be found in Appendix A.

Overall, comparing the diesel results with the trolley results, a decrease of approximately 37% in fuel consumption is observed before trolley line relocation, followed by an approximate 31% decrease after moving the line. After relocating the trolley segment to the outer pit shell, the trolley line segment is longer, and the electricity consumption roughly doubles. In total, compared to the diesel only scenario, the energy cost with trolley assist is reduced with 14% before moving the line and with 6% after moving the line. Combined with the M&R costs, this leads to the 3% and 2% difference in mining costs for diesel and trolley assist before and after line relocation respectively.

The results from the cost model are based on estimated material movement, as discussed in section 5.3.4. In the financial model (section 5.6), the total operating costs will be calculated based on the production rates as obtained from the Whittle schedule. The costs represented in Table 5.6 are used as cost inputs in Whittle, so that economic block values can be taken into account during the scheduling process.

5.4. Block Model Preparation

The block model and the pit designs as generated in GEMS, are prepared in Surpac for the export to Whittle. The Ghana Gold case consists of an intermediate pit design, which means that it is assumed that the mine has already been in production. In order to develop a mine plan with trolley assist, starting from the intermediate pit, the block model has to be constrained. Only blocks that are located underneath the intermediate pit topography will be considered during scheduling.

Using the digital terrain model file (.dtm file) of the intermediate pit surface, a block model constraint can be formulated in Surpac. The result of applying this constraint to the block model, is shown in Figure 5.5 on page 38. This constrained block model can be directly exported from Surpac to Whittle.

To account for the trolley line, additional modification of the block model is required. To prevent Whittle from mining the blocks underneath the trolley line haul road, the blocks have to be given a high mining cost adjustment factor (MCAF) of 1000. Whittle can process a time-dependent MCAF for various rock codes. Therefore, the haul road blocks must be given a different rock code from the rest of the deposit. This is done

Table 5.6: Key operating and capital cost outputs from the cost model.

Scenario	Cost Item	Unit	Period 1	Period 2	Period 3	Period 4	Period 5
Scenario 1	**Operating Costs**						
	Mining	$/t	1.93	1.93	1.93	2.13	2.14
	Mining + Milling	$/t	4.81	4.81	4.81	4.17	4.18
	Capital Costs						
	Trolley Line Installation	$M	4.3	0	0	1.2	0
	New Trucks	$M	40.9	0	0	15.3	0
	Retrofit Trucks	$M	2.5	0	0	0	0
	Substations	$M	2.9	0	0	0.7	0
	Relocation Trolley Line	$M	0	0	0	0.1	0
	Total (new trucks)	$M	48.1	0	0	17.3	0
	Total (retrofit trucks)	$M	9.7	0	0	17.3	0
Scenario 2	**Operating Costs**						
	Mining	$/t	1.93	1.93	1.93	1.93	2.15
	Mining + Milling	$/t	4.81	4.81	4.81	4.81	4.19
	Capital Costs						
	Trolley Line Installation	$M	4.3	0	0	0	1.2
	New Trucks	$M	40.9	0	0	0	15.3
	Retrofit Trucks	$M	2.5	0	0	0	0
	Substations	$M	2.9	0	0	0	0.7
	Relocation Trolley Line	$M	0	0	0	0	0.1
	Total (new trucks)	$M	48.1	0	0	0	17.3
	Total (retrofit trucks)	$M	9.7	0	0	0	17.3
Diesel Only	**Operating Costs**						
	Mining	$/t	1.99	1.99	1.99	2.16	2.18
	Mining + Milling	$/t	4.88	4.88	4.88	4.20	4.21
	Capital Costs						
	New Trucks	$M	38.4	0	0	14.4	9.6

by creating polygons on the haul road segments, and editing the the rock type attribute of the block model within these polygons. An example of this polygon and its affected blocks is shown in Figure 5.6. The same process is repeated for the final pit outline, to prevent Whittle from producing pit designs outside the final pit limit. Table 5.7 gives an overview of the rock codes present in the exported block model. In Appendix C, a more detailed breakdown of the work done in Surpac is included.

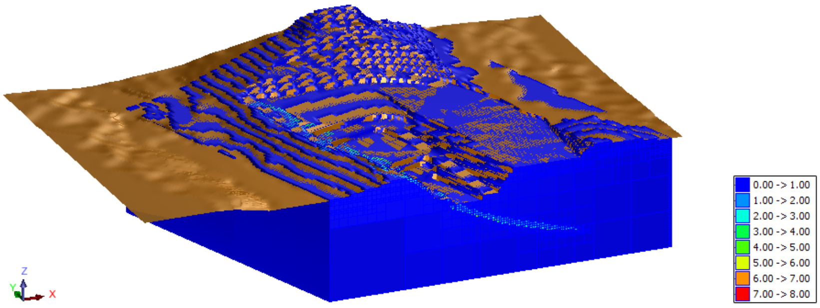


Figure 5.5: 3D section view of the IP surface constrained block model, showing the gold grade of the blocks. The block model is 1450 meter wide along the X-axis.

Table 5.7: Original and additional rock codes from the Standard Rock Type attribute in Surpac.

Rock Code	**Description**
102	Standard rock type, transitional
103	Standard rock type, fresh
501	Haul road blocks on segment 3, pit floor to crusher
502	Haul road blocks on segment 5, pit floor to waste dump, before moving the line
503	Haul road blocks on segment 5, pit floor to waste dump, after moving the line
601	Blocks outside the final pit limit (on the X,Y plane)

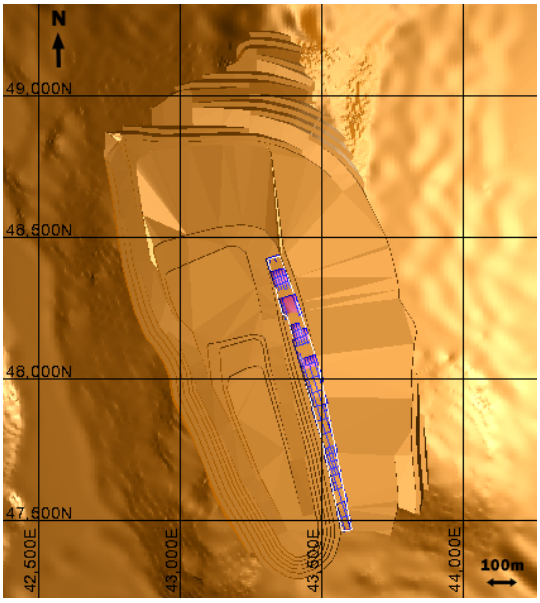


Figure 5.6: Plan view of the constrained haul road blocks for haul segment 5 (rock code 502), from the pit floor to the waste dump, before relocation of the trolley line.

5.5. Scheduling

The resulting block model is used to determine the optimum schedule for different scenarios. From Surpac, a model file and a parameter file of the constrained block model are exported to Whittle. The following section describes the work done in Whittle.

5.5.1. General Settings

The block model is imported without reblocking it, so that the block dimensions remain: X = 10, Y = 25 and Z = 10. The unit of mass for rock data is tonnes, the currency is set to US dollars and the ore elements are reported in grams. The period length is set to six months. To account for the final pit limit from the initital pit design, the block model must be constrained in Whittle. The maximum depth of the final pit is reached at a Z coordinate of -15 (corresponding to block index Z=21), thus the tonnage region of the block model has been limited by a minimum Z index of 21.

The block model exported from Surpac distinguishes between the six different rock types (Table 5.7). All gold grades have been exported as "standard", and renamed "Au" in Whittle. Figure 5.7 is a visual representation of the imported block model.

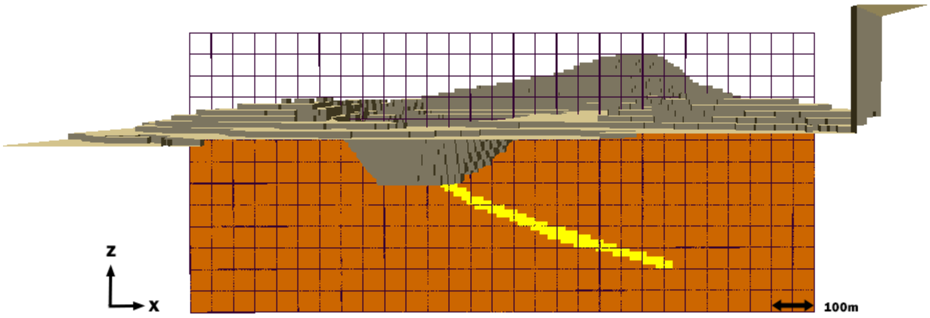


Figure 5.7: Section of the constrained block model in Whittle on the X,Z plane at Y=45. The yellow color represents ore, brown represents waste. The bottom left block indices are X: 1, Y: 45, Z: 1. The bulge on the right side of the section is due to an inconsistency in the intermediate pit topography. The bulge can be neglected, because it is located outside the block model and therefore does not have impact on the pit.

5.5.2. Pit Shell Generation & Operational Scenario

For the intermediate pit block model, two scenarios have been generated, as discussed in section 5.3.4. In the first scenario, the trolley line on the hanging wall will be moved in the fourth period (one period being six months). In the second scenario, the movement of the line will be delayed with one period relative to the first scenario.

These scenarios form two separate branches in Whittle, each containing three different nodes with pit shells that are generated based on the block values. The three nodes distinguish between the diesel only scenario, the trolley scenario with new trucks and the trolley scenario with retrofit truck configuration. These separations are made because of the different operating and capital costs that are related to the diesel and the trolley assist configurations. In the pit shell node, the basic operating costs (mining, processing and selling) are defined. The optimization is set to the tonnage region as defined in the general settings, in order to prevent Whittle from extracting blocks with a Z index lower than 21. This constraint prevents Whittle from mining beyond the depth of final pit design. Additionally, the increased MCAF for the blocks outside the final pit limit in the X,Y plane is set, to prevent Whittle from mining outside the final pit outline.

The pit shell generation node is closely related to its underlying operational scenario node. The operational scenario copies the costs defined in the pit shell node, but allows for time-dependent inputs. Therefore, the different operating and capital costs that resulted from the cost model (Table 5.6 on page 37), can be entered. For each of the periods where there is no specific cost specified, Whittle will use the basic cost as defined in the pit shell node.

The operational scenario node is the most important node for trolley assist. Not only does it enable the user to enter time-dependent costs, it also allows for a time-dependent MCAF for each rock type. Therefore, this is the step where the constrained haul road blocks under the trolley line are added to the equation. Similar to the cost inputs, the MCAF can be specified for each period. The standard MCAF is set to 1. For both the diesel and trolley assist scenarios, the MCAF of rock type 601 is set to 1,000 for all periods. For diesel, the MCAF of the other five rock types remains 1. For trolley assist, the MCAF is dependent on the scenario and period. Because the trolley line on the foot wall side is permanent, the MCAF for rock type 501 is 1,000 for all periods in both scenarios. In Scenario 1, rock type 502's MCAF is set to 1,000 during periods 1 until 3, and changed back to 1 in period 4. The MCAF of rock type 503 is set to 1,000 starting in period 4. For Scenario 2, the MCAF of rock type 502 is set to 1,000 in the periods 1 until 4, and changed back to 1 in period 5. Rock type 503's MCAF is set to 1,000 starting in period 5.

Another important feature of the operational scenario node is the possibility to define mining and milling limits. Based on the Ghana Gold data set, the mining limit is set to 35 Mtpa and the milling limit is 4 Mtpa. This translates to a maximum 17.5 Mt per period for mining and 2 Mt per period for milling.

5.5.3. Pit by Pit Graph

For each operational scenario, a pit by pit graph is created. This graph shows the total, cumulative mineable rock tonnage (waste and ore) for the generated nested pit shells, based on the mining and processing limits that are set in the operational scenario and the pit shell generation. The pit by pit graph of trolley assist Scenario 1 is shown in Figure 5.8, a complete overview of the graphs is included in Appendix D.

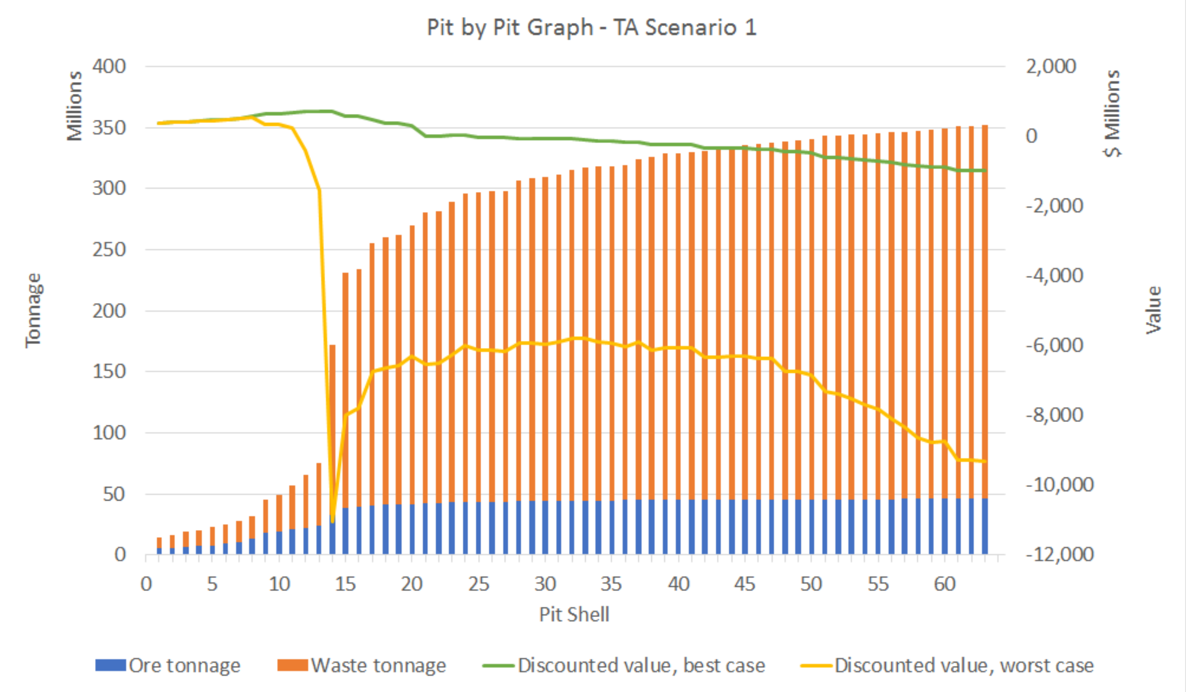


Figure 5.8: Pit by pit graph of the TA pit shell set from Scenario 1, with a 35 Mtpa mining limit and a 4 Mtpa processing limit. The graph is based on the Whittle pit by pit output.

The pit by pit graph is used to determine the optimum ultimate pit limit, by comparing the NPV with ore and waste tonnages. The lines represent the discounted value of the best and worst case. From an NPV perspective, the ultimate pit limit is the pit shell on the point where the discounted value curve starts leveling out. For the Ghana Gold case, the ultimate pit has already been defined in the pit designs. Therefore, the pit shell that is most closely related to the final pit design is chosen as the ultimate pit limit. This is not necessarily the most suitable pit shell according to the NPV curves.

It is evident from the graph, that pit 14 and further require significant extra material movement. The curves level out rapidly, and even drop to major negative values. Normally, pit 13 would be chosen as final pit limit, but because of the objective of assessing the difference in NPV of Scenario 1 and Scenario 2, the final pit limit is chosen based on its depth and outline. This is done by viewing the pit shells in 3D, resulting in an ultimate pit limit of pit 15. This pit is the first in the pit by pit sequence to match the depth and shape of the final pit design. Hence, it meets the final pit requirements, with the minimum amount of material to be extracted (although the extracted amount of material is significantly higher than with a pit limit of 13). The outline of pit 15 is shown in Figure 5.9.

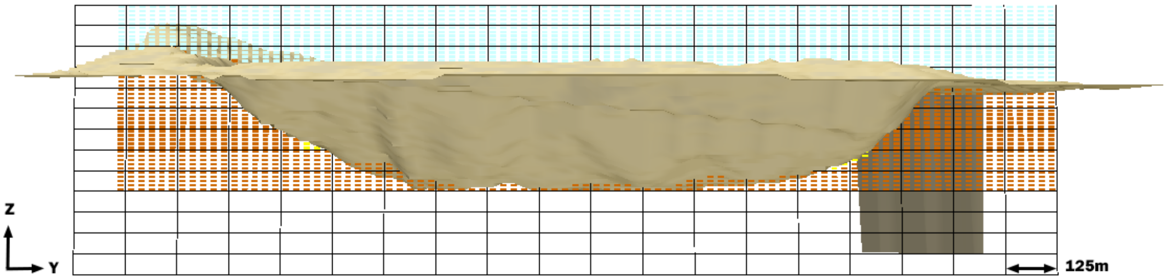


Figure 5.9: Section view of pit shell 15. Blue blocks indicate air, brown blocks indicate waste and yellow blocks indicate ore.

5.5.4. Schedule

After generating and assessing the pit by pit graph, and selecting the ultimate pit limit, a schedule is created for each operational scenario. The schedule can be generated for the worst, specified or best scenario from the operational scenario. The ultimate pit limit as determined from the pit by pit graph is the input for the user specified final pit. In this case study, the specified case is used for all scenarios, as it allows for manual selection of the scheduling algorithm and pushbacks.

There are different scheduling algorithms available in Whittle. In this project, the Milawa NPV algorithm is used for all scenarios. This algorithm automatically calculates the best sequence to approach the best case scenario (see section 4.3), optimizing the NPV over the life of mine. For trolley assist, the pushbacks are selected manually, based on the leaps in rock tonnage in the pit by pit graph. Minimum and maximum lead (i.e. number of benches from the adjacent pushback that can already be mined in the current pushback) are adjusted manually, in order to achieve an appropriate schedule that matches the trolley line movement. For diesel, there are no constraints in pushbacks or leads. Therefore, the automatic pushback selection from Whittle is used, without specifying minimum and maximum lead. The resulting pushbacks are: pit 3, pit 13, pit 14 and pit 15.

From section 5.5.3, pit 15 is selected as the ultimate pit. This pit is in accordance with the final pit design parameters. Within the Milawa NPV mode, there are four pushbacks selected for trolley assist: pit 1, pit 9, pit 13 and pit 14. The minimum and maximum lead are used to force Whittle to follow the steps as described in Scenario 1 and 2. Because of the different shape of the pushbacks, the leads vary per pushback. The Milawa NPV specified case parameters are listed in Table 5.8. The automatic pushback selection for the diesel only scenario is also set to four pushbacks.

Table 5.8: Whittle Milawa NPV parameters for the TA scenarios, with final pit 15.

Pushback	**Pit**	**Minimum Lead**	**Maximum Lead**
1	1	1	4
2	9	2	3
3	13	3	5
4	14	3	5

Because the objective of the Whittle schedule is to produce an optimum NPV, with the additional specification of mining to the predesigned final pit, the cut-off grade is not specified beforehand in the base case. Given the constraints as discussed above, Whittle automatically selects the most suitable cut-off grade, based on the cut-off grades per pit shell. This results in a cut-off grade of 0.494 gram per tonne for the base case. In Chapter 6, the impact of changes on the cut-off grade will be assessed.

With these settings and inputs, a schedule graph is generated for each of the operational scenarios. The data from the Whittle schedule graphs can also be represented numerically, and is exported to the financial model in Excel, where further calculations on the NPV are performed. The schedule graphs and results will be presented in section 5.7.

5.6. Financial Model

Although the schedule generated in Whittle includes a value for the NPV of the scenario, it is more accurate to manually calculate the NPV in the financial model, for example by adding taxes including depreciation. In Whittle, schedules have been generated for many different scenarios. Hence, the financial model is required to produce the NPV for many different scenarios as well. Each of the selected Whittle schedules is assessed separately, by determining the periodical gold production, rock tonnage movement and the NPV.

5.6.1. Gold Production

The numerical mine schedule as produced in Whittle, is exported to the financial model in Excel. The key data that need to be obtained from the mine schedule are the amount of ore and waste mined per period, and the average gold grade of the ore that enters the processing circuit. The total amount of rock mined per period is the sum of the ore and waste, which is used to calculate the total mining costs. The amount of ore mined and its average grade are used to determine the periodical revenue.

The amount of gold produced is calculated from the amount of ore processed, the gold grade and the gold recovery. The tonnes of ore milled can be directly extracted from the Whittle schedule, as well as the average gold grade per period. A gold recovery of 91% is assumed, being the median value of gold recovery from the initial nine Ghana Gold ore rock codes. The gold grade is defined as gram per tonne. The gold price is commonly expressed in $ per troy ounce. Therefore, the amount of gold produced is expressed in troy ounces.

5.6.2. Net Present Value

The purpose of the financial model is to determine the Net Present Value of the specified case. The NPV is calculated step-by-step, determining revenue, operating cost, capital cost and after tax cash flow, for each of the operational scenarios. Based on the gold production, calculated as described above, the periodical revenue can be determined. A gold price of $1200 per troy ounce and Net Smelter Return of 87% are assumed.

The operating expenditure (OPEX) is based on the costs as determined by the Cost Model (section 5.3). Mining and G&A costs are defined as $/tonne of total rock, whilst milling and selling costs are defined as $/tonne of ore. The selling costs consist of royalties and refining costs, which can be calculated after the gold production is determined. Royalties are assumed to be 5% of the revenue, in accordance with PwC [36]. Based on the periodical production of total rock tonnes and ore (calculated as described above), the mining, milling, G&A and selling costs can be determined separately, after which they are summed to define the total OPEX per period.

The capital expenditure (CAPEX) for the diesel scenario consists only of truck purchases. For the trolley assist scenario, the installation and relocation of the trolley line is allocated as a capital expenditure, as well as the purchase of new trolley trucks or retrofit trolley packages.

With the revenue, OPEX and CAPEX defined per period, the theoretical profit per period can be determined. Based on the taxable income, the after tax cash flow is calculated. The taxable income consists of the revenue less the operating costs and depreciated capital costs. In Ghana, a straight line depreciation with a rate of 20% is assumed for machinery in the mining industry, according to PwC Ghana [37]. With a tax rate of 35% [37] for mining companies, the income tax is calculated. In case of a negative income, loss is not carried forward.

The total after tax cash flow consists of the revenue less the operating costs, tax and capital expenditure. The NPV is calculated based on the after tax cash flow, with equation 3.1 and a yearly discount rate of 8% [38].

5.7. Results

In this section, the results of the above described scheduling and NPV calculation steps for the two trolley assist scenarios are presented and interpreted. In addition, the results of a diesel only operation versus a trolley assist operation will be presented and discussed.

5.7.1. Scheduling Results

In Scenario 1, the trolley line was moved during the fourth period of six months. In Scenario 2, the trolley line was moved during the fifth period of six months. All scenarios had a mining limit of 35 Mtpa, a processing limit of 4 Mtpa and an ultimate pit limit of pit 15.

The schedule graphs for the two trolley assist scenarios and the diesel scenario are presented in Figure 5.10. The schedule graphs show the amount of ore and waste rock mined and processed per period, as well as the average gold input grade. Since stockpiles have not been considered for this case, the amount of ore processed is equal to the amount of ore mined. The period has been set to six months. Figure 5.10a shows that during period 4, approximately 6.5 Mt of waste will be mined, compared to only 5 Mt in Figure 5.10b. This is due to the delay in relocation of the trolley line in Scenario 2, which forced the schedule to leave the ramp in place for one period longer than in Scenario 1.

The amount of ore mined is the same for Scenario 1 and 2, with a small difference in average grade over the first five periods. Scenario 1 shows an early peak in gold grade, and quickly drops to a lower, more constant level after period 3. Scenario 2 shows a more fluctuating average gold grade in the first five periods, with two high peaks in period 2 and 4. The suspension of the trolley line relocation does not seem to further impact the schedule. The diesel only schedule resulted from an automatic Milawa NPV run in Whittle. Compared to the trolley assist scenarios, this schedule shows a lot more fluctuation in the amount of waste mined. However, the fluctuations in rock tonnage occur in all three scenarios. Therefore, they are due to geologic characteristics of the deposit, such as the ore grade distribution and the shape of the orebody, in relation to the selection of ultimate pit 15.

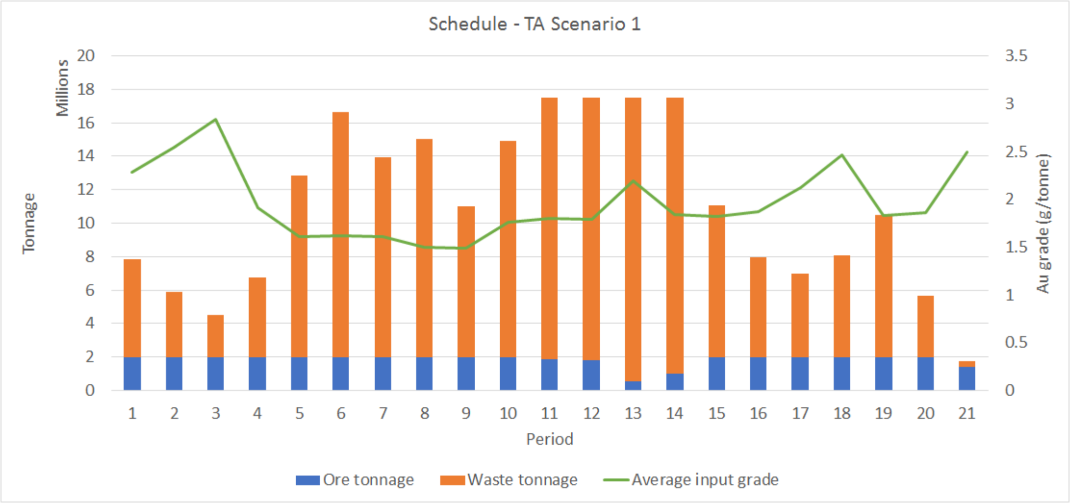
It is evident from the schedule graphs, that the Milawa NPV mode prioritized a constant amount of ore mined above a constant amount of total rock tonnage. Almost all periods show an optimum amount of ore mined (in accordance with the processing limit of 2 Mt per period), except around period 13, 14 and 21. Since the drop in ore tonnage around period 13 occurs in all three scenarios, it is likely due to similar geologic characteristics in the block model.

5.7.2. Financial Results

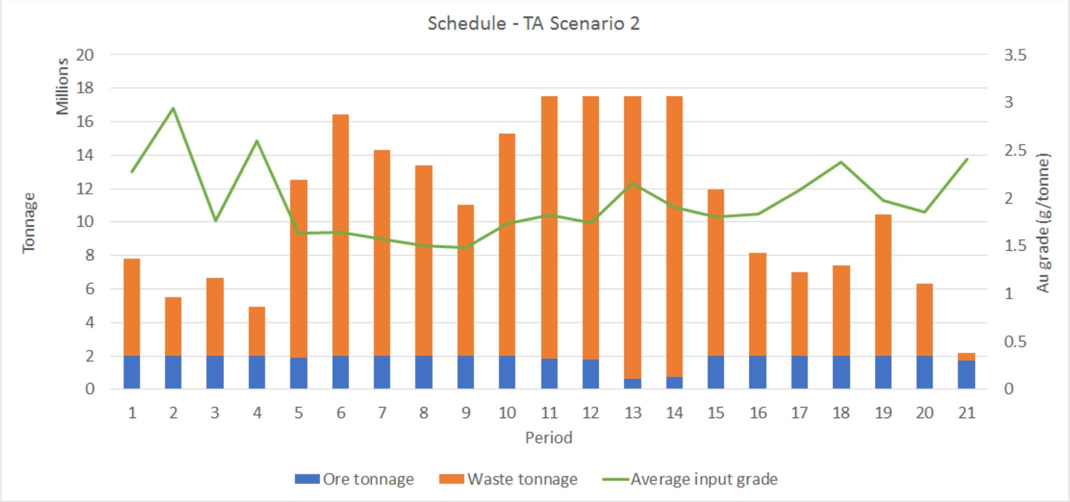
The scheduling results from Whittle were used for the calculation of the NPV in the financial model, as described in section 5.6. Detailed calculations from the financial model can be found in Appendix E. The operating costs, revenues, capital costs and after tax cash flow were calculated per period.

Figure 5.11 on page 45 presents the periodical revenues and operating expenses for the diesel and TA scenarios. It shows a highly fluctuating OPEX for diesel, against a slightly more stable OPEX for trolley assist. From Figure 5.10, it can be concluded that the ore input remains fairly equal over the life of mine (except around period 13, 14). Thus, there is not much fluctuation in milling and selling costs. Logically, this means that the fluctuations are due to variations in mining costs. This corresponds with the inconsistent amount of total rocks mined, as noticed in Figure 5.10.

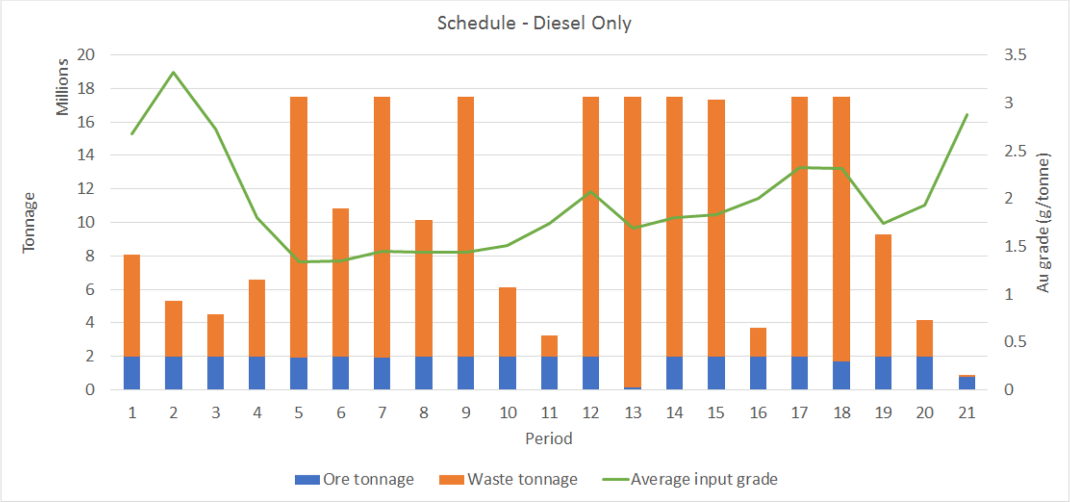
Since the trolley assist OPEX fluctuates less than the diesel OPEX, the amount of total rock tonnage mined is likely better distributed in the trolley assist scenarios than in the diesel scenario. This clearly shows in Figure 5.10 as well. As the diesel only schedule is generated using the automatic Milawa NPV mode, it can be considered the best approach to achieve an optimum NPV (using the manually selected ultimate pit limit). However, the schedules that were used to calculate the NPV, are not a fair representation of realistic mine schedules, due to the high fluctuations in material mined.



(a)



(b)



(c)

Figure 5.10: Schedule graphs for (a) trolley assist scenario 1, (b) trolley assist scenario 2 and (c) the diesel only scenario, based on the Whittle schedules. One period is six months.

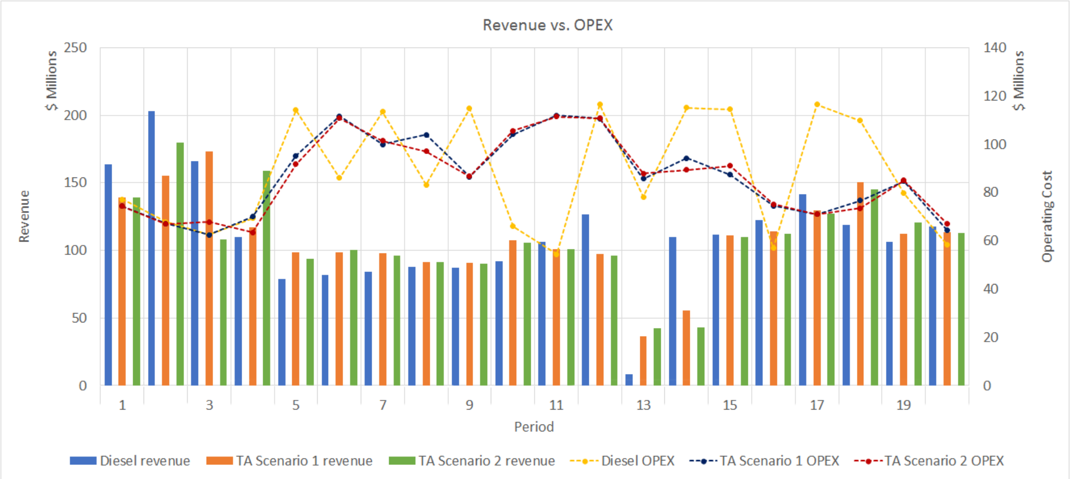


Figure 5.11: Periodical revenues and OPEX for the diesel scenario and the two TA scenarios. Revenues are displayed on the primary Y-axis (left), operating costs on the secondary Y-axis (right).

Furthermore, trolley assist Scenario 1 and 2 show a fairly similar OPEX. This means that the delay of moving the trolley infrastructure has very little effect on the overall periodical operating costs. This is due to the fact that the amount of material mined per period is roughly comparable between the two trolley assist scenarios (see Figure 5.10).

The total operating cost of the diesel only scenario is 1,778 $M, while the total operating cost of the trolley assist scenarios are 1,776 $M and 1,777 $M for Scenario 1 and 2 respectively. The difference in revenue between the two scenarios is a bit more distinct. This is due to the fluctuation in average gold grade, since the periodical amount of ore input is equal between both scenarios (as observed in Figure 5.10a and b). The total revenue of the diesel scenario is 2,293 $M as opposed to 2,299 $M for the TA scenarios.

Based on these revenues and costs, the after tax flow per period was calculated. The NPV was determined over the entire life of mine, in years rather than periods, based on the yearly discount rate. The NPV results are presented in Table 5.9 on page 45.

Table 5.9: Net Present Values resulting from the financial model. All scenarios have a mine life of 10.5 years.

Scenario	**NPV ($M)**
TA Scenario 1	148.4
TA Scenario 2	149.6
Diesel Only	156.4

It is evident from Table 5.9, that the diesel only scenario results in the highest NPV. The lower capital costs for diesel and the early occurrence of higher revenues, are probably the most significant reason for the difference in NPV. Although the operating costs do show a difference in favor of the TA scenarios, it is not substantial enough to offset the change in revenue and additional capital expenditure.

The comparison between trolley assist Scenario 1 and 2, shows that Scenario 2 results in a slightly better NPV. This is likely due to the fact that, while the total revenue and capital expenditure is equal, Scenario 2 gives a marginally higher revenue in the first four periods and delays the capital costs with one period relative to Scenario 1. The operating costs are almost equal, but slightly in the benefit of Scenario 2. The change in occurrence of the revenue and capital costs works in favor for the *"one dollar today is worth more than one dollar tomorrow"* principle of the Net Present Value (see section 4.1). However, as these changes are only minor in nature, the difference in NPV between Scenario 1 and 2 is insignificant.

In addition to the trolley assist scenarios in which a complete new fleet of haul trucks is purchased, the possibility of retrofitting the existing truck fleet with trolley packages was assessed. The retrofit configuration is based on the assumption that the required amount of trucks is already available and that they are trolley capable. This assumption causes a CAPEX reduction of almost 80% in the first period, relative to the purchase of complete new trolley trucks. This results in an NPV of 182.1 $M for Scenario 1 and 182.5 $M for Scenario 2.

However, since the operational circumstances of the Ghana Gold operation are unknown, the retrofit configuration has not been considered for further analysis. To assess the impact of retrofit trucks, the details of the original truck fleet should have been known. The comparison is merely included to show that it can be advantageous to consider trolley assist from the start of the operation, for instance by buying trolley capable trucks instead of mechanical-drive trucks for the initial haul fleet. When trolley assist is implemented after the first couple of years, the ability to retrofit trolley capable trucks with a trolley package prevents extra capital expenditure for completely new trucks.

6

Sensitivity Analysis

In the previous chapter, the impact of trolley assist on strategic mine planning of the Ghana Gold case has been assessed. Key parameters of the assessment, such as cost and price inputs, are based on assumptions and estimates. In this chapter, a sensitivity analysis on six key parameters will be performed. In addition, the impact of the cut-off grade on the operation will be assessed.

The purpose of the sensitivity analysis is to identify which factors and assumptions are most critical for the project's NPV and feasibility of the trolley assist system. The sensitivity analysis consists of six changes for each of the individual inputs, which are ordered systemically in steps of 5%, ranging from -15% to +15%. In the first section of this chapter, the inputs and results of the sensitivity analysis on these six parameters will be presented, followed by an individual evaluation per parameter. The second section comprises a separate sensitivity analysis on the cut-off grade, which focuses on specific values rather than percent changes relative to the base case.

6.1. Key Parameters

The six key parameters that will be assessed are the electricity price, the diesel price, the gold price, utilization of the trolley line, the overall slope angle of the pit and the length of the initial trolley line on the waste (hanging wall) side. The inputs for each of these parameters is listed in Table 6.1. For the sensitivity analysis, trolley assist Scenario 2 with new trucks is used as the base case. To identify the most critical parameters for the Ghana Gold case study, the results are combined into one graph, shown in Figure 6.1. Based on this graph, each parameter will be discussed in the following section. An overview of the numerical results of the sensitivity analysis can be found in Appendix F.

Table 6.1: Inputs for the sensitivity analysis of the six parameters on the NPV of the Ghana Gold case.

Parameter	**Unit**	**-15%**	**-10%**	**-5%**	**Base Case**	**+5%**	**+10%**	**+15%**
Electricity price	$/kWh	0.145	0.153	0.162	0.170	0.179	0.187	0.196
Diesel price	$/L	0.85	0.90	0.95	1.00	1.05	1.10	1.15
Gold price	$/oz	1,020	1,080	1,140	1,200	1,260	1,320	1,380
Trolley line utilization	%	72	77	81	85	89	94	98
Slope angle	°	38	41	43	45	47	50	52
Trolley segment length	m	850	900	950	1,000	1,050	1,100	1,150

6.1.1. Electricity Price

By replacing a part of the diesel fuel consumption by electric energy, the price of electricity becomes an important variable in the operating costs. It is important to assess the impact of changes to the electricity price on the NPV, as the electricity price is not a fixed parameter. The balance between the electricity price

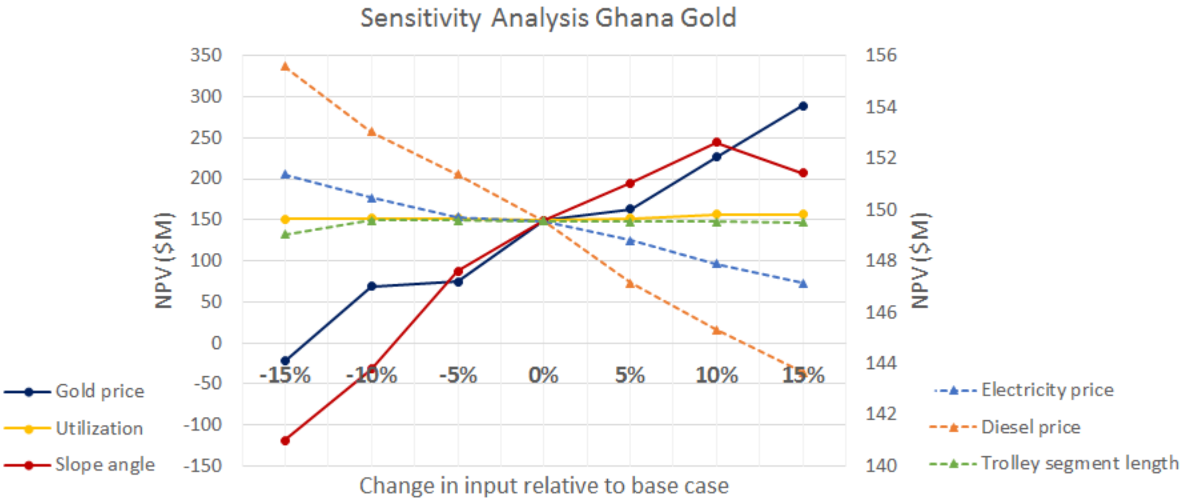


Figure 6.1: Graphical representation of the results of the sensitivity analysis on the six key parameters for Ghana Gold. The curves for the gold price, utilization and slope angle belong to the primary Y-axis (left). The curves for the electricity price, diesel price and length of the trolley segment belong to the secondary Y-axis (right).

and the diesel price is believed to be a crucial factor in achieving a gain in operating costs that can be offset against the capital investments of the trolley system.

An electricity price of \$0.170/kWh is used in the Ghana Gold case, based on the current electricity price for large open pit mines in Ghana. The values for the electricity price, as presented in Table 6.1, are adjusted in the cost model. With these new operating costs, the NPV is calculated in the financial model.

From Figure 6.1, it can be concluded that the NPV of the Ghana Gold project is not very sensitive to the electricity price. The difference in NPV between the lowest and the highest electricity price (i.e. -15% and +15% from the base case) is only 4.3 \$M. This is likely due to the relatively small changes in energy cost, compared to the total operating costs. In the base case, the electricity cost accounted for only 26% of the total energy cost and only 2% of the total operating costs. Overall, the changes in total electricity cost have little impact on the total operating costs. This translates into a slightly decreased NPV when the electricity price increases, and a slightly increased NPV when the electricity price decreases.

6.1.2. Diesel Price

The potential savings that can be made on energy costs are also dependent on the diesel price. This case study uses a diesel fuel price of 1.00 \$/L. Comparable to the electricity price sensitivity analysis, the inputs from Table 6.1 are used in the cost model, modifying the mining costs per period. The new NPV is determined with the adjusted costs in the financial model.

Compared to the electricity price sensitivity, the diesel price sensitivity shows a clearer impact on the NPV. However, the total impact remains relatively small, with a total difference of 11.9 \$M between the lowest price of 0.85 \$/L and the highest price of 1.15 \$/L. Similar to the electricity price, this is probably because the energy costs only form a small share of the total operating costs. Nevertheless, it can be concluded that the NPV of a trolley assisted mine is more dependent on the diesel price than on the electricity price.

6.1.3. Gold Price

In combination with the amount of ore processed and the gold grade, the gold price determines the periodical revenue, which in turn is offset against the operating and capital costs to determine the NPV. By decreasing or increasing the gold price, the revenue will decrease or increase as well. In addition, it might affect the schedule, because of the change in economic value per block. Therefore, the variation in gold price is adjusted in the Whittle model and in the financial model.

The changes in the mine plan as result of the sensitivity analysis are presented in Table 6.2. It is evident that the changes in the gold price have a major effect on the mine planning process and result. With an adjusted gold price, the set of pit shells that is generated is considerably different from the base case. This also affects periodical production and life of mine.

Table 6.2: Overview of the changes in the mine plan parameters and NPV, occurring when modifying the gold price.

Parameter	**Unit**	**-15%**	**-10%**	**-5%**	**Base Case**	**+5%**	**+10%**	**+15%**
Ultimate Pit	#	20	18	16	15	13	12	11
Life of Mine	years	10.5	11.5	11.5	10.5	11.5	11.5	13.5
NPV	$M	-21.7	69.4	74.8	149.6	163.5	226.2	289.5

In Figure 6.1, it can be seen that the gold price is one of the most sensitive parameters of the trolley assist project. With the lowest gold price of this sensitivity analysis, the value of the project drops with more than 170 $M, to a negative NPV. With the highest gold price, the project gains almost 140 $M on the NPV. Especially for a trolley project, where extra capital investment is involved, revenue is a key factor. An increase in the gold price, would result in a quicker payback of the trolley assist system, whereas a decrease in gold price will make it more difficult to earn back the investment. Since the gold price is highly volatile to changes on the market (i.e., supply and demand), it is considered a key critical parameter for the success of the Ghana Gold case.

6.1.4. Trolley Utilization

The utilization of the trolley line is essential in achieving increased performance with trolley assist. When the line utilization is low, it will be difficult to offset the capital trolley expenditure against the operational benefits. It is very important to note that trolley line utilization is a highly variable factor, which can change from day to day. Situations affecting utilization are related to e.g. the maximum number of trucks that can be engaged to the line, the number of available haul lanes on the ramp and the mechanical availability of the trolley attachment on the truck. These situations mostly depend on daily operating conditions. If the trolley line is not used on a very frequent basis, it is expected that the gain on operational savings might not be enough to offset the capital investment. Therefore, analyzing and quantifying the impact of a range of different utilization factors is essential in assessing the feasibility of trolley implementation.

For the Ghana Gold case, a utilization of 85% was assumed, based on average performance at Kansanshi. Utilization of the trolley system influences the mining costs, and potentially imposes changes to the capital (truck) costs as well. In this case, the production target remains the same, leaving utilization only to affect the number of required trucks, as opposed to an increased productivity with the same amount of trucks. The resulting changes in operating and capital costs are used in the financial model, to calculate the new NPV.

From Figure 6.1, it can be concluded that, against expectations, the adjusted utilization does not pose a large effect on the NPV of the Ghana Gold project. The operating costs experience little to no changes, which is likely due to the fact that the energy costs are only a small part of the total operating costs. Since the cycle times only experience a relatively small reduction with trolley assist, the production rate remains fairly unaffected as well. With a higher utilization (+10%, +15%), there is a saving of one truck after relocating the line, resulting in a one-time saving of 5.1 $M in the fifth period.

6.1.5. Slope Angle

As discussed in section 4.4, the slope angle is of high influence on the design and planning of an open pit mine. Since the slope angle is based on estimated rock behavior, prone to geotechnical risk, and the width of benches and ramps, it poses uncertainty to the mine design. For the Ghana Gold case, a standard overall slope angle of 45 degrees was assumed, with a ramp width of 60 meter. By performing a sensitivity analysis on the slope angle, it can be assessed how much changes in the slope angle, and thus in ramp width, affect the feasibility of the trolley assist system.

The slope angle can be adjusted in Whittle. Within the same block model, different slope sets can be defined. By changing the slope angle, Whittle will generate complete new sets of pit shells, which means that the mine design could be significantly different from the base case. For this sensitivity analysis, the final pit limit, as provided in the Ghana Gold case, still forms the boundary of the pit design.

Table 6.3: Overview of the changes in the mine plan parameters and NPV, occurring when modifying the slope angle.

Parameter	**Unit**	**-15%**	**-10%**	**-5%**	**Base Case**	**+5%**	**+10%**	**+15%**
Ultimate Pit	#	18	16	15	15	15	14	13
Life of Mine	years	12	12.5	12.5	10.5	10.5	10.5	10.5
NPV	$M	-118.7	-31.9	87.3	149.6	194.7	244.3	206.8

Table 6.3 lists the altered mine planning parameters, resulting from the changed slope angles. It is evident that the slope angle has a considerable influence on the mine design. Figure 6.1 shows that, from the selected parameters, the changes in the slope angle could lead the project to the most negative NPV. Because the final pit outline remains as it is, the decrease in slope angle limits the amount of ore that can be extracted. This translates into the sharp drop of the NPV. Vice versa, an increased slope angle means that less waste must be mined to reach the ore, resulting in an increased NPV.

If the other bench geometry parameters remain equal, the decrease in slope angle is due to an increase of the ramp width. Theoretically, the 5% change in slope angle corresponds with a change of approximately 18 meter in ramp width. Therefore, for trolley assist the +5% change in the slope angle is of particular interest. Changing the ramp from 60 meter to 42 meter would roughly meet the triple lane versus dual lane configurations. From Table 6.3 it can be seen that this scenario leads to a 45 $M increase in NPV. This difference is only due to the change in slope angle, and does not take into account the operational alterations that will occur when switching from a triple lane to a dual lane haul road with trolley assist.

The difference between the best and worst NPV performance when adjusting the slope angle, amounts to 363 $M. This is the largest range of NPV of the six analyzed sensitivities. Therefore, slope angle and ramp width form a very critical factor in the feasibility of trolley assist in the Ghana Gold project. However, considering the ramp width, changes of more than 5% from the base case scenario are not very likely to occur.

6.1.6. Trolley Segment Length

The initial length of the trolley line segment on the waste dump side of the pit, is 1 km. The objective of the sensitivity analysis on the trolley segment length, is to assess the impact of a longer or shorter trolley haul on the NPV. The total length of the haul profile remains the same. By changing the travel distance on trolley, the cycle times will be affected, which in turn influences the productivity. In addition, the distance traveled on trolley will impact the fuel and electricity consumption. Potentially, this sensitivity analysis could show if there is a preferable optimum trolley segment length, that leads to the best performance of the mine.

Modification of the trolley segment length influences haul costs and truck productivity, potentially affecting the operating costs. Because of the length-dependent installation costs of the trolley assist system, the capital costs are influenced as well. Hence, the changes for this sensitivity analysis are made in FPC, in the cost model and in the financial model. This sensitivity analysis only looks at the effect of changing the trolley line segment length, without taking into account the changes that could be imposed on the haul road design.

The sensitivity curve of the trolley segment length (on the right Y-axis in Figure 6.1) shows an almost flat trend. The changes of maximum 150 meter in potential distance on the trolley line, do not affect the mining costs. This is likely due to the relatively small impact of diesel fuel and electricity expenses on the total mining costs, causing the shifts in the diesel and electricity balance to be redundant. The changes in uphill haul time are only a small portion of the total cycle time, so the influence on truck productivity and required number of trucks is minimum.

The small differences in NPV are due to the changes in capital expenditure on the trolley system. The main impact of decreasing or increasing the length of the trolley line can be attributed to the installation of (extra) substations. However, within the 15% range, there is no need for less or more substations. Therefore, changes in capital costs are directly related to the cost per kilometer of trolley line. This causes the small effect on the NPV.

6.2. Cut-Off Grade

As discussed in section 5.5.4, a cut-off grade (COG) that was automatically generated by Whittle was used for the base case schedules. Adjusting the cut-off grade could result in major changes in the pit shell generation. It could also drastically alter the total amount of material to be extracted, and therefore pose significant changes in the schedule and NPV. Because the percentage changes as used in the previous sensitivity analyses do not result in meaningful adjustments in the cut-off grade, four specific changes will be assessed: one COG lower than the base case and three COG's higher than the base case. The values are selected from the grade tonnage graph of the constrained block model, see Figure 6.2. The automatically selected cut-off grade for the base case is 0.494 g/tonne.

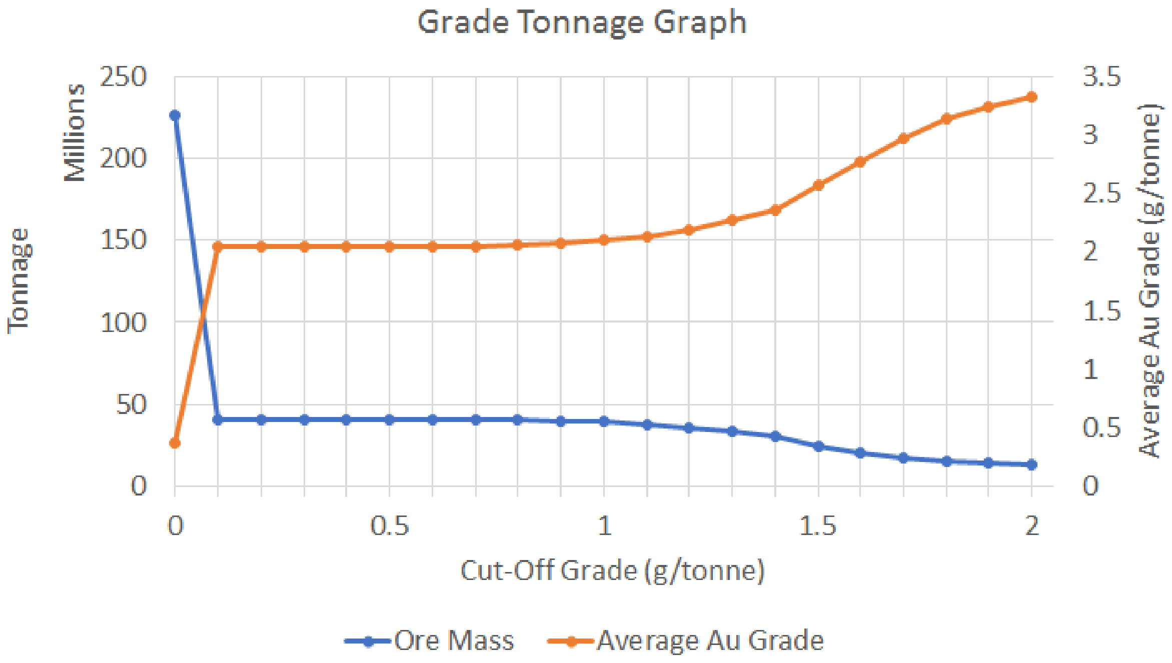


Figure 6.2: Grade tonnage graph of Scenario 2. The primary Y-axis (left) shows ore mass in tonnes, the secondary Y-axis (right) shows average gold grade in gram/tonne.

The alternative cut-off grades for the sensitivity analysis are: 0.1 g/tonne, 1.0 g/tonne, 1.5 g/tonne and 2.0 g/tonne. At these cut-off grades, the curves of the ore mass experience a notable change, see Figure 6.2. In Whittle, new pit shell sets are generated with these cut-off grades. Because the cut-off grade will affect the amount of material to be extracted, new ultimate pit limits and pushbacks have to be determined.

Table 6.4: Overview of the changes in the mine plan parameters and NPV, occurring when modifying the cut-off grade.

Parameter	**Unit**	**COG 0.1**	**Base Case**	**COG 1.0**	**COG 1.5**	**COG 2.0**
Ultimate Pit	#	15	15	15	19	29
Life of Mine	years	10.5	10.5	10.5	12	8.5
NPV	$M	149.6	149.6	153.2	-87.1	-135.6

The results of the cut-off grade sensitivity analysis are listed in Table 6.4. A graphical representation with respect to the base case is presented in Figure 6.3 on page 52. A cut-off grade of 0.1, lower than the automatically selected cut-off grade, gives the same results as the base case. Hence, the base case of 0.494 g/tonne is assumed to be the minimum cut-off grade. A raised cut-off grade of 1.0 g/tonne increases the NPV with a very small amount. Cut-off grades higher than 1.0 g/tonne drastically decrease the NPV. Therefore, 1.0 g/tonne can be considered the optimum cut-off grade, even though the change with respect to the base case is negligible.

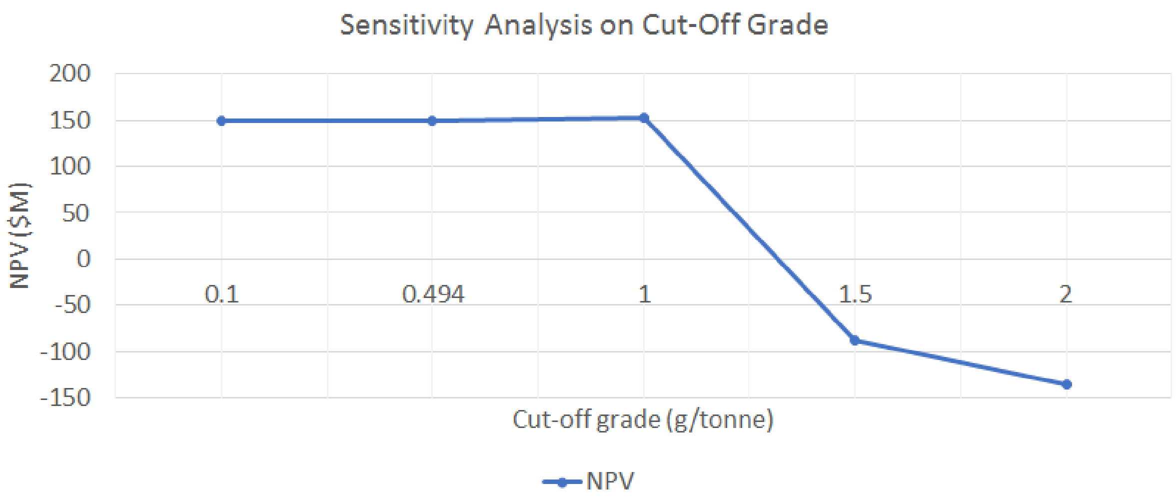


Figure 6.3: Sensitivity graph of the cut-off grade of the Ghana Gold project. The cut-off grade of 0.494 is the base case scenario.

7

Discussion

This research was conducted to assess the impact of the implementation of trolley assist on strategic mine planning. In particular, by evaluating the balance between the frequency of movement of the system and the operational savings that can be achieved. By means of a case study, the approach of incorporating trolley assist characteristics in strategic mine planning was investigated, with the aim of finding the maximum NPV. More specifically, the effect of relocating the overhead trolley lines on the NPV was assessed, to identify the balance between the movement of the trolley infrastructure and the operational savings of the trolley system.

The case study was performed on a theoretical case, concerning an Archean gold deposit in Ghana. The Ghana Gold case comprises an active operation. The assessment of the impact on the implementation of a trolley system, focused on the operation between a given intermediate and final pit. Two scenarios for trolley assist were investigated, considering relocation of the system in different periods. In addition, a diesel only scenario was generated. A sensitivity analysis was conducted on seven parameters, to assess the project's sensitivity to changes is the values of these parameters.

In this chapter, the obtained results are assessed on their validity and applicability within this research. The suitability and use of the Ghana Gold case, the cost model and the software play an important role in the case study. Therefore, these subjects will be discussed alongside the validity of the obtained results from the case study. The purpose of the discussion is to assess how the methodology and results fit into the hypothesis and theoretical background as described in Chapter 2, 3 and 4.

7.1. Suitability of the Ghana Gold case

The Ghana Gold case was specifically created for this research. It was decided to investigate a moderately dipping, tabular orebody, as it would result in an intermediate pit design with a permanent foot wall ramp and a temporary hanging wall ramp. The use of Cat 795F AC trucks would normally not be the optimal choice for this kind of operation, because of the size of the mine. Therefore, the gold grades were manipulated to increase the revenue of the operation and to allow for the capital and operating costs of large haul trucks.

The case study consisted of an intermediate and final pit design. The intermediate pit served as the starting point for this research. Since Ghana Gold is a theoretical case study, no operational parameters from the initial mining process were available. Ghanaian cost parameters were used for the case study. Compared to South-African prices, the electricity price was fairly high. This has a major effect on the savings generated from operating a trolley system. The truck energy (fuel and electricity) and M&R costs were calculated using the cost model, whereas all other mining and processing costs were obtained from SNL Metals and Mining [35] for similar operations.

The Ghana Gold block model was a very complex model, containing twelve different rock types, all with different characteristics. Since the research required a more simplistic approach to mining, e.g. with a limited amount of haul profiles and without mining block selectivity, it was decided to only take into account the block model gold grades, without considering the different rock types. All rock mass was considered to have the same characteristics.

Because there were two main haul roads present in the intermediate pit design, the foot wall ramp was appointed as ore haul route and the hanging wall ramp was selected for waste haulage. Since the ore haul route is located on a permanent ramp, it was suitable for a permanent trolley line. Since the aim of the research was to investigate the impact of moving the trolley line, the waste haul route on the temporary hanging wall ramp was suitable for the installation of a flexible trolley line.

7.2. Cost Model Validity

The cost model is fundamental to the strategic mine planning process and formed a major part of this research. Therefore, the validity of the cost model is important in the interpretation of the results. Since the cost estimates are associated with a significant amount of uncertainty, the outputs should be dealt with accordingly.

The cost model was created before the detailed yearly production rate of the mine was obtained. Therefore, all calculations are based on a rough production estimate. Normally, the cost model and the scheduling process act as an iterative system. The productivity results obtained from the scheduling process, when using the initial costs, serve as a new input for the cost model. The renewed costs are used for a second series of scheduling, resulting in an (potentially) altered productivity. This process can be repeated multiple times, until the cost model input closely matches the schedule output. Due to time constraints, it was not possible to iterate the cost model and scheduling process. Therefore, the accuracy of the costs that are used in Whittle and in the financial model is debatable. Although the impact of iteration leads to a change in operating costs of only a few cents per tonne, the total operating costs could increase or decrease with significant amounts.

The cycle times and productivity were determined based on the haul profiles. Realistically, there are many haul profiles in a mine, as rock has to be transported from multiple working faces. This means that there is a high difference in haul distance, for example between a truck that transports rock from the pit floor to its destination and a truck that transports rock from one of the upper working benches. Incorporating many haul profiles would have added a lot of complexity to the cost model, and would have caused a deviation from the aim of this research.

Furthermore, the shift roster from the cost model does not account for seasonal changes in scheduled (truck) hours and production rate. Considering the tropical climate of Ghana, it is not very likely that the mine will be able to uphold the production rate of the dry season in the wet season as well. As a result, the scheduled trucks hours will differ per season. From practice, this could mean that the trolley line cannot be used throughout the entire year, as the ramps are not able to accommodate large and heavy haul trucks during the wet season. Smaller trucks are a suitable replacement of large haul trucks in this situation, but they are unable to make use of the trolley line. Because of the complexity of this season-dependent constraint, it was excluded from the research scope, and a continuous annual production with large haul trucks was assumed. However, a situation like this will have a major impact on the feasibility of a trolley system, since it drastically impacts the utilization of the trolley trucks and trolley lines.

The estimation of the capital costs of installing and moving the trolley infrastructure is a very important aspect of the cost model. There is limited data available on this topic, and there are very high differences in the numbers that are reported. The capital costs are dependent on the country of installation, in terms of material and labor, and on the vendor or contractor of the system. Because there are no trolley assist operations in Ghana yet, the cost estimates are rather uncertain. In the Monte Carlo analysis, the most likely costs were assumed to be the estimates based on Kansanshi, adjusted for Ghanaian circumstances. The minimum and maximum costs were obtained from Swedish and Canadian literature. A more detailed investigation in specific material costs, labor costs and expected installation time in Ghana is expected to result in a more accurate cost estimate, and would therefore increase the level of certainty of the NPV calculation.

In the cost model, it is assumed that the implementation of trolley assist results in a reduced truck fleet. In section 3.7, increased production was introduced as another potential way of creating benefit out of trolley assist. As the Ghana Gold case concerns an active operation, it is likely to assume that the rest of the fleet (e.g. the loaders) and the processing facility are not designed for handling increased production. Significant additional capital expenses would have to be made, in order to accommodate for a higher throughput of material. This would add more complexity and uncertainty to the cost model. Furthermore, there was no data available on the initial Ghana Gold operation. The capacity of the processing facility and total mine fleet was unknown. Hence, the reduced truck fleet scenario was considered a better fit for this research.

7.3. Model Preparation & Scheduling

The Ghana Gold data set was provided in GEOVIA GEMS. For the block model preparations, GEOVIA Surpac was used. The block model attributes were stored in four different folders in GEMS, based on the rock types present in the model. In the "standard" folder, an attribute containing the total gold grade was incorporated. In Surpac, the attributes per rock type could not be combined into one attribute. Normally, it is crucial to transfer all attribute data into the block model. However, since it was decided that all rock types were to be treated equally for this case study, the use of the "standard" attributes (containing the total gold grade per block), was sufficient.

In Surpac, the block model was constrained by the intermediate pit surface. Because the final pit design was another constraint, on the bottom of the block model, it was attempted to constrain the block model by the final pit as well. Unfortunately, because the topography from outside both pit designs was equal, this double-constrained model did not transfer well into Whittle. Therefore, it was decided to account for the final pit constraint by changing the MCAF on the blocks outside of the final pit in Whittle, and by limiting the tonnage region to the deepest block index of the final pit design. Hence, the intermediate pit constraint was incorporated in the Surpac model and the final pit constraint was added in the Whittle process. This approach to the problem was considered to be an adequate solution for the Ghana Gold case, but would likely not be suitable for detailed mine planning procedures.

By changing the rock codes of the trolley haul road blocks in Surpac, these segments could be given an artificially high MCAF in Whittle, to prevent them from being mined. This method proved to be a suitable solution to the time-dependent haul road block constraints. However, this method can only be used if the exact location and design of the (trolley) haul road is known. Therefore, the assessment on relocation of the trolley line will likely take place in one of the later stages of mine planning.

The annual mining and processing limits were chosen based on the size of the Whittle results from the initial Whittle analysis (before the pit design took place), and the size of the haul trucks. From a practical perspective, it is not likely that a mine with these production rates would use trucks the size of a Cat 795F AC. A larger fleet of smaller trucks would probably result in a smoother production, and potentially in a higher NPV.

7.4. Validity of the Results

The results, as presented in section 5.7, show that the diesel only scenario results in the highest NPV, closely followed by trolley assist Scenario 2 and Scenario 1 respectively. Since there was less capital investment required for the diesel only scenario, it is a logical result that this generated the highest NPV. However, the difference between the NPV of the diesel only scenario and trolley assist scenario 2, is only 7 $M, which is a negligible amount on a total NPV of approximately 150 $M. In addition, the potential benefit of a lower CO_2 emission has not been taken into account.

7.4.1. Cost of Carbon

As discussed in section 3.7.3, the increasing focus on the impact of the emission of greenhouse gases is leading towards carbon pricing incentives, i.e. putting a price on CO_2 emission with the aim of reducing carbon pollution. In assessments from Newmont [39] and PMR [40], calculations on the cost of carbon have been carried out. For the Ghana Gold case, the reduction of 37% on fuel consumption (before trolley line relocation) corresponds to saving more than 2 million liters of fuel per period. As 2.7 kg CO_2 is emitted with the combustion of 1 liter diesel fuel, this translates into a decrease in CO_2 of 5,400 tonne per period, i.e. 10,800 tonne per year. Assuming a carbon price of 50 $/tonne [39], this means that a minimum of 0.54 $M can be saved on a yearly basis, relative to the diesel only scenario. After relocating the trolley line, the decrease in fuel consumption rises to more than 3.3 million liters, corresponding to a minimum annual saving of 0.89

$M. Adding this cost of carbon to the operating costs, the NPV of the diesel only scenario will drop to a level below the NPV's of the trolley assist scenarios. Besides this economic benefit of trolley assist, the decrease in carbon emission is valuable for the sustainability of the mining operation as well.

7.4.2. Cost Fluctuation

In Figure 5.11, it was seen that both the diesel scenario and trolley assist scenarios suffer from fluctuating operating costs. In section 5.7, it was discussed that this effect was likely due to the inconsistency in amount of rock mined per period. The trolley assist OPEX showed a bit more stable behavior than the diesel OPEX. This was attributed to the higher inconsistency in mined tonnage in the diesel only scenario, relative to the trolley assist scenarios. The extracted rock tonnage is directly dependent on the pushback and bench selection. The pushbacks for the trolley assist scenarios were selected manually, based on the pit by pit graph. For the diesel only scenario, the pushbacks were automatically selected by Whittle. Since the fluctuating behavior of material mined was noticed in all three scenarios, it was concluded that it was due to the combination of geologic characteristics of the deposit and operational requirements related to the desired shape of the mine.

Opposed to the fluctuating amount of waste mined, the schedules showed a fairly constant ore production rate. This constant tonnage is a logical result from using the Milawa NPV mode in Whittle. The Milawa NPV algorithm prioritizes maximizing ore tonnage mined over total rock tonnage mined, to assure a constant revenue. While this approach may have resulted in the optimum achievable NPV, it produced very unrealistic mine schedules in this case. In order to mine a constant ore tonnage with a fairly constant average grade, inconsistent amounts of waste had to be mined. This relates to the shape of the orebody and the gold grade distribution.

Although the diesel only scenario shows a higher fluctuation in total tonnage, the amount of ore tonnage is more constant, compared to the trolley assist scenarios. Combined with the higher average grade that is achieved with diesel only, this translates in a higher and more stable revenue, which can also be seen in Figure 5.11. Especially in the first periods, and around period 13 and 14, this is noticeable. This is likely the reason that, despite the fluctuating OPEX, the diesel only scenario performs slightly better on the NPV.

In the financial model, the mining costs between period 6 and the final period, have been interpolated for both diesel and trolley assist. The costs of the final period are determined with the haulage profiles from the final pit, and the continuation of the M&R rate based on unit truck hours. In this cost model calculation, the production rate has been assumed to remain constant throughout the years, resulting in a constant unit truck hour rate. However, as the Whittle schedules also demonstrate, the production is not constant, and therefore the interpolated mining costs are not a true reflection of the real costs. Still, since the deviation is likely not more than a few cents per tonne, the overall effect on the NPV will be minor.

7.4.3. Fleet Configuration

For the assessment of trolley assist, two configurations were assumed: the purchase of new trucks and using a retrofit trolley package for the trucks that are already in operation. This distinction was made because the Ghana Gold case concerns an active operation. However, since there was no operational data on the original fleet for the Ghana Gold mine, the retrofit configuration was not assessed in detail and was not taken into account in the NPV comparison between diesel only and trolley assist.

If trolley assist is considered during an early stage of mine planning, it can be decided that trolley capable trucks are purchased, even though the actual implementation of trolley will occur after a certain period of time. This will decrease the capital investment that is required when installing the trolley system, as confirmed by the results of the case study. However, this general assessment did not take into account that retrofit trucks are in a later stage of life than new trucks, and will therefore have a different availability and M&R rate. Nevertheless, the use of retrofit trolley packages may be an advantageous solution for mining operations that have considered trolley assist during early stage mine planning. Of course, this is only interesting if a mine would have used mechanical-drive or other non-trolley capable trucks. It must be noted that the retrofit configuration represents a fairly limited reality, considering the existence of mixed haul truck fleets and the procurement process of large haul trucks.

The costs used for the Ghana Gold case, were mostly related to haul trucks. Other cost items, such as overhaul of auxiliary equipment or the purchase of extra equipment (other than trucks), have not been taken into account. The basic mining cost might cover a part of the operating costs of other equipment, but these costs have not been investigated in detail. Therefore, the NPV does not give a true reflection of the project's economics and feasibility.

7.4.4. Trolley Assist Scenarios

For the Ghana Gold case, two trolley assist scenarios were assessed. These scenarios were generated to investigate the effect of the period of time in which the trolley infrastructure is relocated. In this research, the relocation was delayed by one period, being six months. The changes that this suspension caused in NPV, were negligible.

The relocation periods were chosen based on the optimum schedule that was automatically generated by Whittle for the diesel only scenario. For the first scenario, the relocation of the trolley line followed the natural progress of the mine design from the unconstrained scenario. For the second scenario, the relocation was postponed with one period relative to the first scenario. From the schedules, it was concluded that this caused a slight decrease in amount of waste rock mined, due to the ramp that had to be left in place during period 4. The downtime of the trolley assist system caused by relocation of the line, was accounted for by decreasing the trolley line availability. This had no noticeable effect on the periodical operating costs. The duration of relocation was assumed to take 4 weeks, whereas the costs and schedule were determined as an average over 6 months.

If the research would have used shorter periods of time, for example on a week-by-week or month-by-month basis, the delay of trolley line relocation might have shown clearer results on the exact effect on the costs and schedule. It must be noted, that by scaling down the periods of time, the level of detail increases. Considering the uncertainty of the cost and production estimates that were made for the Ghana Gold case, such a detailed assessment would not have been suitable for this project.

7.4.5. Sensitivities

In Chapter 6, seven parameters were assessed on their criticality for the project's performance. The two most critical parameters that were identified, were the gold price and the slope angle. Both parameters required a renewed pit shell generation, potentially altering the production rate, ultimate pit limit and life of mine. The changes in gold price would have a similar effect on a diesel only operation. However, since trolley assist requires significant extra capital investment, the revenue plays a more important role in payback for the system. A lower gold price will drastically affect the feasibility of a trolley assist system. Variations in the slope angle would also show comparable results on a diesel operation. However, in this case the +5% change in slope angle was associated with a change in ramp width of 18 meter. This roughly corresponds to changing the triple lane haul road to a dual lane haul road. It is a logical outcome that narrowing the haul road results in an increased NPV, as it leads to a decrease in stripping costs. Since the Ghana Gold mine is considered to be in operation already, the other changes in slope angle are not very likely to occur.

The electricity price, diesel price and utilization turned out to have minimum impact on the project's NPV. For the electricity and diesel price, this was likely due to their small share in the overall operating costs. In an assessment that only looks at the haul costs, these changes could likely be investigated in more detail. The length of the trolley segment also showed a minimum impact on the NPV. Because the the changed lengths did not require the installation of an additional substation, the extra capital costs were relatively low. The gain or loss on operating costs was insignificant, related to the small share of the electricity and diesel costs in the overall operating costs. Against the expectations, the utilization of the trolley line did not cause a significant impact on the NPV. Similar to the other negligible parameters, this was likely caused by the small share of fuel costs in the overall operating costs. The increase of utilization would result in the abundance of one truck, which resulted in a one-time saving after the trolley line relocation. Relative to the total capital expenditure and operating costs, this was only a minor saving, without noticeable impact on the NPV. In case of the increased production scenario, as discussed in section 3.7, the changes in utilization might have caused a more meaningful effect. With a decreased productivity as a result of low trolley line utilization, the revenue might be directly affected when the ore production falls short. As noticed in the sensitivity analysis of the gold price, a decrease in revenue may cause a significant decrease in NPV.

7.5. Reflection

The hypothesis of this thesis was that incorporating the benefits and limitations of trolley assist in the optimization of the long-term mine plan is a key factor in achieving an increased NPV with trolley assist. The case study comprised an active mining operation, with a fixed intermediate and final pit design.

In the Ghana Gold case, the diesel only scenario led to the highest NPV, which does not support the hypothesis. However, the differences in the NPV between diesel and trolley assist were minimum and potential future benefits of trolley assist, such as the cost of carbon, were not taken into account. The two trolley assist scenarios that were assessed, showed slightly different results (although with only minor changes in NPV). This supports the hypothesis that including trolley assist in the optimization of the long-term mine plan can assist in determining the optimum mine plan. However, as the changes in NPV for this case study were insignificant, they cannot be considered a full justification nor opposition of the hypothesis.

The main weakness of this research was the provided dataset for the case study. The complexity of the Ghana Gold case caused substantial constraints in preparing the block model and generating realistic mine schedules. This resulted in significant delays in the research process, limiting the study in terms of available time for e.g. an iterative cost model or the investigation of more scenarios. Other limitations of this research concerned the insufficient availability of solid cost data and the lack of information on the operational conditions of the Ghana Gold mine.

Due to these limitations, it was not possible to investigate the possibility of increasing productivity instead of downsizing the haul truck fleet. However, in light of the results of this case study, the increased productivity scenario might have yielded a more distinct outcome. Increased productivity would have caused substantial changes to the schedule, resulting in altered NPV's. Furthermore, modification of e.g. the utilization or length of the trolley segment could have influenced the ore production rate, and hence the revenue. This would have likely resulted in a more significant alteration of the NPV, compared to changes in operational expense only.

The strength of this study was the formulation and implementation of the methodology to account for fixed haul roads accommodating a trolley segment. Using time-dependent mining cost adjustment factors for the particular haul road blocks, indicated with a different rock code, proved to be an adequate approach to the Ghana Gold case. This methodology is expected to be suitable for other cases as well, as it did not depend on specific behavior of the Ghana Gold case. However, this methodology does require detailed data on the location of the trolley lines. This poses a *chicken or the egg* dilemma for mines without an already existing mine plan, with the location of the trolley line being dependent on the mine plan and vice versa. On the other hand, for mines that incorporate trolley assist in an already existing or developed mine plan (like the Ghana Gold case), the methodology is very straightforward.

8

Conclusion

The objective of this thesis was to determine how trolley assist in open pit mining can be accommodated into strategic mine planning, in view of optimizing the NPV. In particular, by determining the balance between frequency of the trolley line movement against the savings generated from operating the trolley system. By means of a case study, the inclusion of trolley assist in the mine planning process was evaluated. The purpose of the Ghana Gold case was to assess the impact of a single relocation of the trolley infrastructure, for two different periods in time, on the mine schedule and NPV.

In this chapter, the conclusions from the literature study and the case study will be formulated. This is done by answering the research questions as phrased in section 2.3, followed by a summary of the key takeaways of this research.

What is the "new" trolley technology that increases the favorability of future trolley implementation?

- Electric-drive trucks have changed from using DC drives to using more powerful AC drives, which resulted in higher possible speed, lower maintenance, increased reliability, better efficiency and more flexibility in engaging to the trolley line.
- Operating costs for the haul fleet have always been accepted as a large expense for open pit mines. Nowadays, deeper and more marginal deposits are being mined, driving companies to look for alternative ways to cut back expenses. Saving on the haul costs by using trolley assist could benefit the feasibility of these challenging operations.
- Increased awareness regarding the emission of greenhouse gases leads to incentives to reduce fuel consumption in the mining industry.
- There have been no indications that trolley assist is only suitable for a specific commodity or deposit type. The feasibility of trolley assist is mostly dependent on economic climate, mine life, productivity and mine plan amenability.

What are likely costs for trolley implementation, with respect to capital investment, and operating and moving the system?

- Cost estimates are highly dependent on the country of interest and mine specific characteristics.
- Costs used in the case study were established by a Monte Carlo simulation on costs obtained from literature and expert estimates.
- When moving the trolley infrastructure, all components of the trolley line can be re-used, except for the permanent mast foundation blocks.

What are extra requirements for infrastructure, maintenance and logistics for trolley implementation?

- Adequate haul road maintenance is key in achieving optimum utilization of the trolley system, as heavy vibration due to uneven surfaces will damage the line and/or the pantograph brushes.
- A triple lane haul road allows trolley trucks to overtake slower, non-engaged trucks, optimizing utilization of the trolley system.
- Maintenance on the trolley trucks requires a skilled work force, with mechanics that have extra electrical proficiency.
- The engine life will be prolonged, postponing the engine overhaul.
- Other components of the truck, such as the final drive and tires, may wear out quicker due to the increased truck speed.

What are the savings generated with trolley assist, where does it occur in the process and how is it realized?

- When using trolley assist, the power in the wheel motors is no longer limited by the maximum power that is generated by the diesel engine. Since the overhead lines deliver more power, the output of the wheel motors is optimized, resulting in a higher speed. The increase in speed leads to a higher productivity per truck, which can be translated into the following two scenarios:
  - Reduced truck fleet size, with savings occurring mainly at the start of the operation.
  - Increased annual production, with savings occurring throughout the mine life.
- With the diesel engine at idle when on trolley assist, considerably less fuel is consumed. This leads to a reduction in operating costs, with savings occurring throughout the mine life.
- The decrease in fuel consumption causes a reduction in CO_2 emission.

By means of a case study, how does trolley assist affect mine planning?

- The diesel only scenario produced the highest NPV.
- The difference in NPV of the investigated scenarios was insignificant (a difference of 8$M between highest and lowest NPV).
- Changes in the mine planning process with trolley assist, consisted of changed operating and capital costs, and haul road blocks that needed to remain in place for a specific amount of time.
- The constraints caused by the trolley line could be accounted for in GEOVIA Surpac and GEOVIA Whittle, by defining new rock codes for the trolley haul road blocks and appointing a time-dependent MCAF for these rock codes.
- By delaying the trolley line relocation with one period, a slightly increased NPV was achieved. However, the schedule and operating costs did not experience significant impact.
- The NPV of the Ghana Gold trolley assist operation was most sensitive to the slope angle and the gold price.

The key takeaway of this research is that the feasibility of trolley assist is not a simple offset between capital investment and operational savings. The impact of trolley assist on the mine plan is of high importance when assessing feasibility. Trolley assist can be accounted for in the mine planning process by raising the mining cost adjustment factor of haul road blocks underneath the trolley line, provided that the location(s) of the trolley line are known. Accurate operating and capital cost data, and the use of short time intervals are critical to a fair assessment of the effect of trolley line relocation on the NPV.

9

Recommendations

In order to fully support the hypothesis as stated in Chapter 2, further research is recommended. This chapter presents the recommendations that resulted from the work that was conducted and the limitations that were encountered during this thesis.

- Due to time constraints, there was no iteration possible between the cost model and the production rates resulting from the Whittle schedules. Since the production rates used in the cost model do not correspond to the results from the schedules, the mining costs are based on inadequate productivity estimates. Therefore, iteration of the production rates and cost model is highly recommended for further research.
- The estimation of the costs poses a significant level of uncertainty on the outcome of the assessment. A more detailed investigation in exact capital and operating costs, would highly increase the reliability of this research. For example, accurate material costs and labor costs obtained from local contractors would improve the level of confidence of the cost estimation. Hence, a more valid NPV comparison can be made.
- In this research, only two trolley assist scenarios were investigated, due to time constraints. Delaying the trolley line relocation by one period of six months did not result in significant differences in NPV. It is recommended to investigate scenarios with a greater delay in relocation, to assess the impact of leaving the haul roads in place for a longer period of time.
- Since the trolley line relocation was assumed to take four weeks, the effect on a six-month interval was small. If the dataset permits, it is recommended to look at shorter time intervals, e.g. month-by-month. This might lead to more distinctive differences in OPEX or schedule between the assessed scenarios.
- In this assessment, the NPV's were calculated using predominantly haul truck related data. A project with a more complete dataset should be used for this assessment, covering all costs that contribute to the total NPV of a project. The dataset should at least include a specific breakdown of the operating costs, to identify the cost shares that will be affected by trolley assist, and to create to possibility to adjust these costs accordingly.
- For the Ghana Gold case, the annual production rate was kept constant, altering the amount of required trucks. For a complete assessment of possible trolley assist scenarios, the savings of increasing production without downsizing the truck fleet should be investigated. This will be an intensive project, because the suitability of the other aspects of the operation has to be investigated as well, for example expanding the processing facility and increasing the production rate of the loaders.
- The Ghana Gold case consisted of an active operation, with a set of predefined mine designs. The implementation of trolley assist was dependent on and constrained by these designs. In order to fully support the hypothesis, it is recommended to conduct similar research on a case concerning an operation that is not active yet (greenfield project), with more flexibility in the mine plan and design.

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A

Cost Model

The cost model is attached as Cost_Model.xlsx. There is a directory within the .xlsx file and an additional overview of the worksheets is listed below. Starting from *4. Ore Production*, the cost model distinguishes trolley assist Scenario 1 and Scenario 2.

Cost_Model.xlsx

1. **Cost Summary**
   Overview of the cost model results. Contains the operating costs (mining and milling) and capital costs for the first 5 periods.
2. **Shift Roster**
   Calculation of the scheduled truck hours.
3. **Haul Profiles**
   Overview of the FPC results for travel time and fuel burn per segment. Also contains the calculations for trolley speed and resulting travel time and fuel burn.
4. **Ore Production**
   Calculation of cycle times and fuel consumption for the ore haul route.
5. **Waste Production**
   Calculation of cycle times and fuel consumption for the waste haul route.
6. **Fleet**
   Calculation of the amount of required trucks.
7. **Maintenance and Repair**
   Calculation of the total maintenance and repair costs, dependent on the life of the trucks.
8. **Operating Costs**
   Calculation of the mining costs: fuel, electricity and M&R costs.
9. **Capital Costs**
   Calculation of the capital costs.
10. **Trolley Line Installation**
    Overview and calculations of trolley specific capital costs, including time and labor.

B

Monte Carlo Simulation

Chapter 5.3 describes the cost inputs that were used in the Cost Model. This Appendix contains the details of the Monte Carlo inputs and simulation of these cost estimates.

Table B.1: 2016 production and cost data of selected mines for the Monte Carlo cost analysis for operating costs. Data obtained from SNL. All costs in US dollars

Cost Item	**Unit**	**Ahafo**	**Akyem**	**Bogoso-Prestea**	**Tarkwa**	**Damang**	**Iduapriem**
Ore mined	Kt/a	5,836.9	8,980.4	1,499.7	14,551.0	2,819.0	5,167.0
Ore processed	Kt/a	7,269.4	8,415.0	1,504.1	13,608.0	4,268.0	5,129.0
Waste mined	Kt/a	29,099.3	24,166.9	4,039.8	86,603.0	16,027.0	22,683.0
Mine - Labor	$/tonne	1.76	1.27	1.81	1.04	1.54	0.71
Mine - Fuel	$/tonne	0.52	0.61	1.16	0.32	0.41	0.53
Mine - Electricity	$/tonne	0.06	0.05	0.29	0.02	0.05	0.05
G&A	$/tonne	0.90	0.52	4.53	0.46	0.63	1.50
Milling	$/tonne ore	17.67	15.74	19.88	11.81	20.04	20.13
Refining	$/oz	3.00	3.00	5.50	3.00	3.00	3.00

Table B.2: Results Monte Carlo simulations. Number of iterations: 1000.

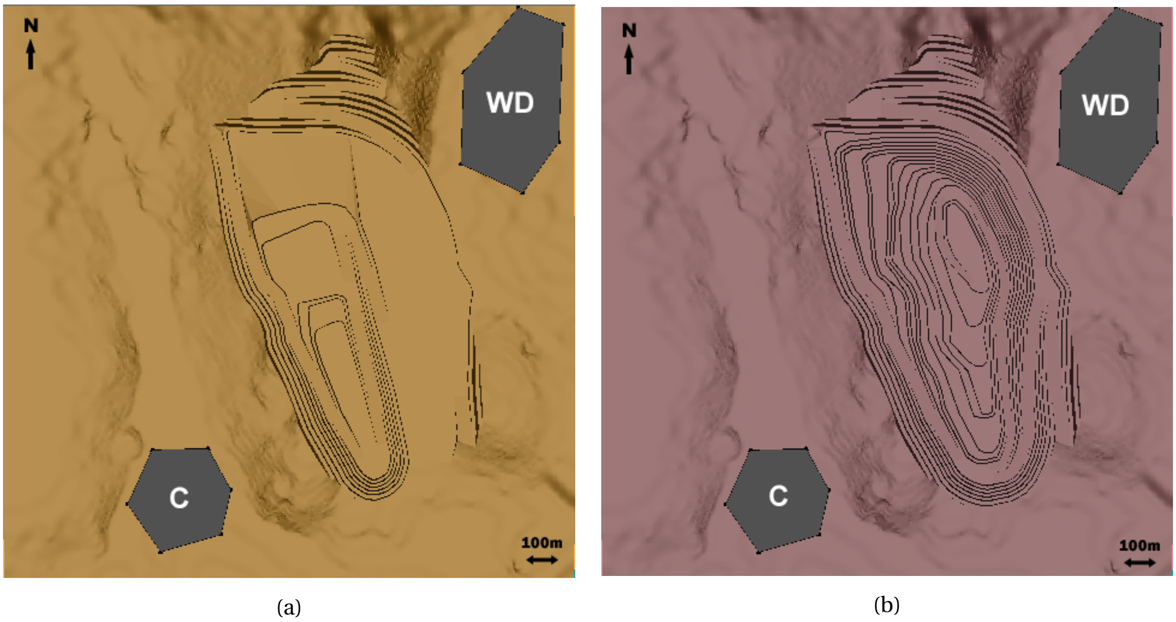
Cost Item	**Unit**	**Minimum**	**Maximum**	**Most Likely**	**Mode**	**Median**	**Standard Deviation**	**Error**	**Simulation Result**
Mine - Labor	$/tonne	0.71	1.81	0.71	0.00	1.04	0.27	0.08	1.09
Mine - Fuel	$/tonne	0.32	1.16	0.53	0.26	0.65	0.18	0.05	0.67
Mine - Electricity	$/tonne	0.02	0.29	0.05	0.10	0.11	0.06	0.02	0.12
Mine - G&A	$/tonne	0.46	4.53	1.50	0.25	2.08	0.88	0.26	2.20
Milling	$/tonne ore	11.81	20.13	20.13	1	17.60	1.93	0.58	17.31
Refining	$/oz	3.00	5.50	3.00	0.00	3.70	0.60	0.18	3.82
Trolley line installation	$/km	1,100,00	2,200,000	1,900,000	0.73	1,752,784	228,116	68,435	1,727,275
DC substation	$/unit	630,000	850,000	700,000	0.32	724,068	46,547	13,964	728,112

C

Block Model Preparations

As discussed in section 5.4, the Ghana Gold block model required additional preparation before exporting it to Whittle. In this Appendix, the preparations will be discussed.

The first step of the preparations consisted of including the crusher and waste dump in the intermediate and final pit design. This was done by drawing polygons in GEMS, which were then transferred into surfaces. The results are shown in Figure C.1. The haulage profiles were determined with the measurement tool in GEMS.



(a)

(b)

Figure C.1: Plan view of (a) the intermediate pit and (b) the final pit, with the waste dump located in the North East and the crusher located in the South West.

The pit designs and block model were exported to Surpac. In GEMS, the block attributes were divided in four different categories (being waste and three rock types). Surpac treated the categories as four separate folders, which could not be combined into one attribute. Therefore, only the standard rock type was used in further adaptions and exports. The gold grades of all categories were captured in the standard rock type, see Figure C.2.

The next step was to adjust the rock codes, in order to account for the trolley segment haul road blocks and the final pit outline. To do so, first the polygons in which the blocks had to be changed, were defined. Using the .dtm file of the intermediate pit, the polygons on the haul road were drawn. The polygons were saved as separate string files. Using the .dtm file of the final pit, the same process was repeated. Figure 5.6 shows the

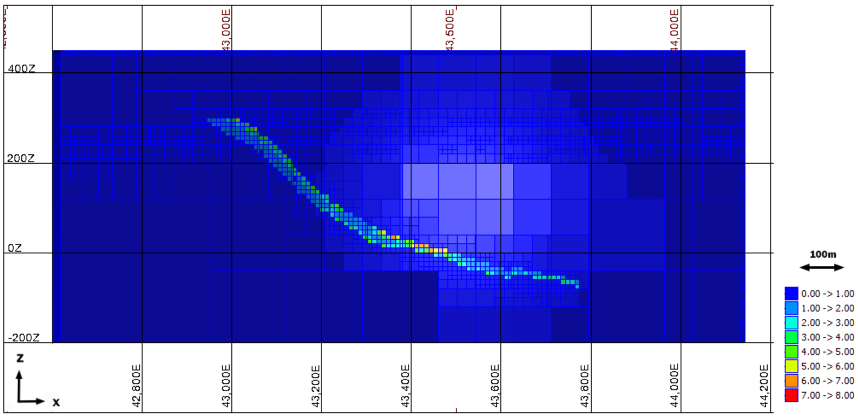


Figure C.2: Cross-section of the Ghana Gold block model.

polygons for rock code 502. The polygons for rock codes 501 and 503 are displayed in Figure C.3. Because a polygon must follow triangulation lines, the 503 polygon ended up a bit wider than necessary. This did not lead to difficulties in the scheduling phase, as this occurred at the outside border of the pit shell.

The string files were used to adjust the rock codes of the block model. This was done with **Block model** > **Attributes** > **Math**, which allowed for the modification of the rock type attribute, using the string files as constraints.

The block model, with the adjusted rock codes, had to be constrained by the intermediate pit surface before exporting it to Whittle. This was by defining a new constraint, removing all blocks above the .dtm surface of the intermediate pit. When exporting the block model via **Block model** > **Block model** > **Export** > **to Whittle**, the block model was exported. With this function, the previously defined intermediate pit constraint could be applied. The attributes that were selected for the export were: standard density, standard rock codes and standard gold grade.

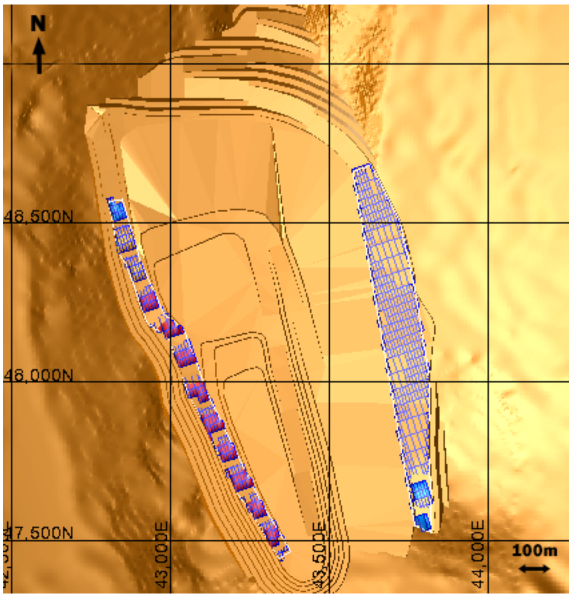
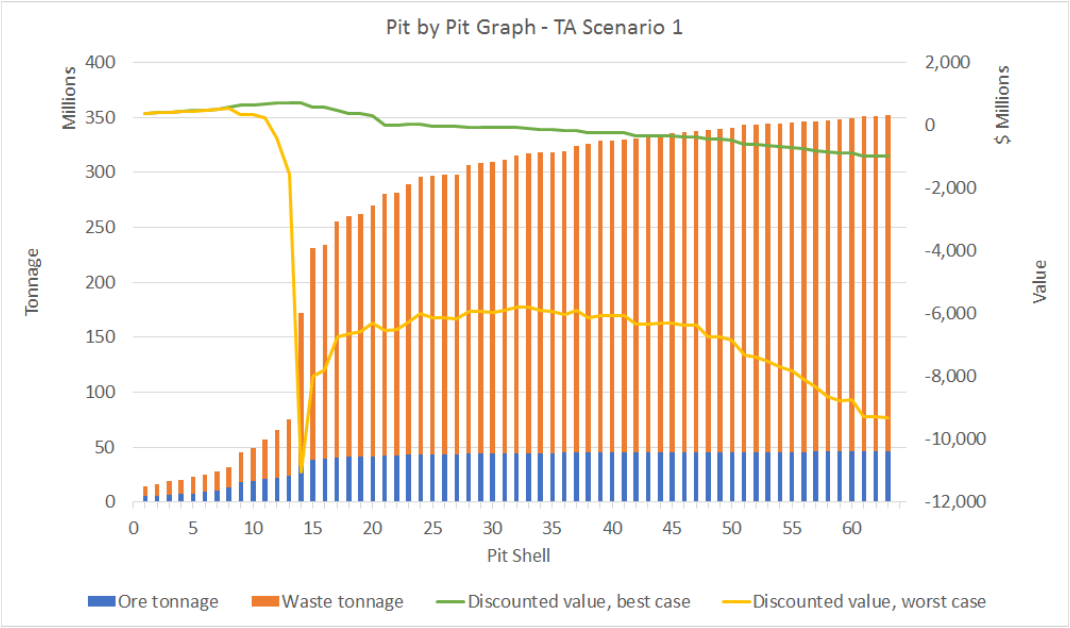


Figure C.3: Plan view of the polygons containing the haul road blocks underneath the trolley line. The left polygon represents the trolley line segment on the ore (foot wall) side, which will receive the rock code 501. The right polygon represents the trolley line segment on the waste (hanging wall) side, after relocation. These blocks will receive the rock code 503.

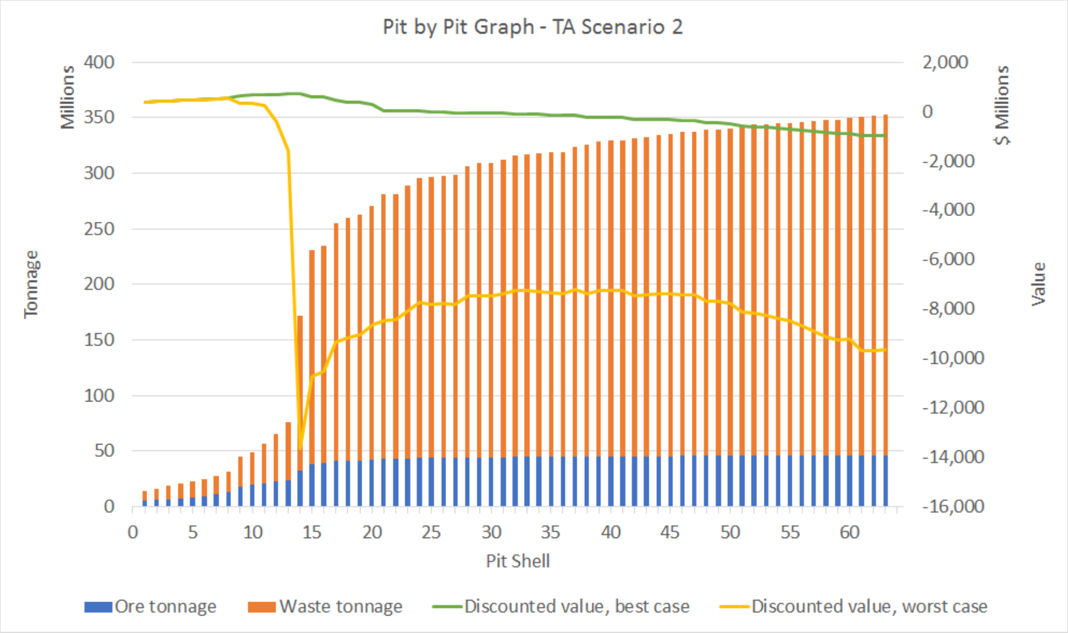
D

Whittle Results

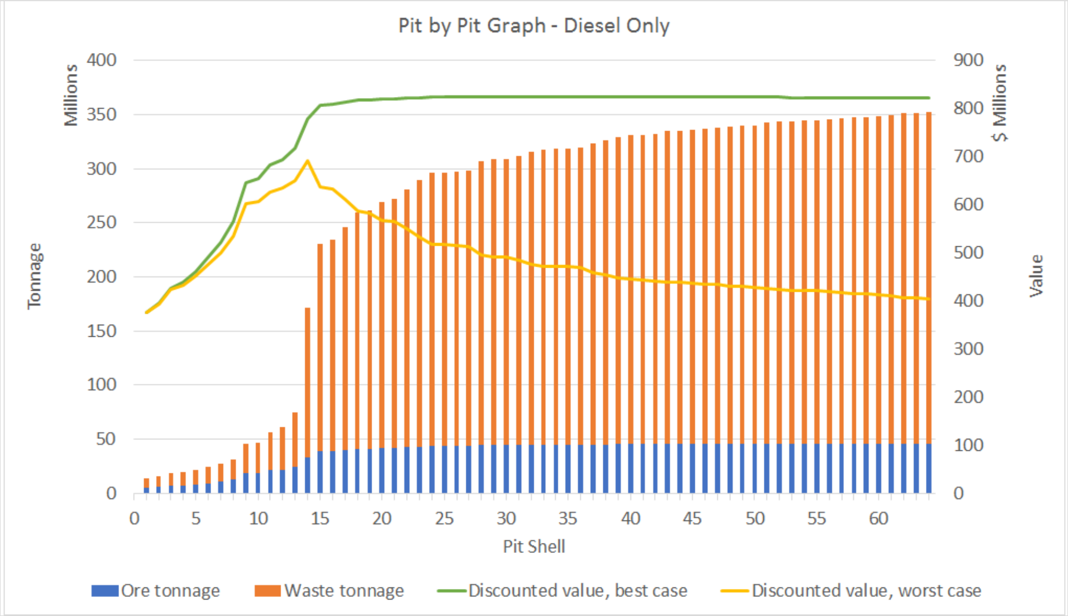
This Appendix contains the pit by pit graphs for trolley assist Scenario 1 and 2, and the diesel only scenario. The pit graphs are made with the output of the Whittle pit by pit generation.



(a)



(b)



(c)

Figure D.1: Pit by pit graphs for (a) trolley assist scenario 1, (b) trolley assist scenario 2 and (c) the diesel only scenario, based on the Whittle pit shell generation.

E

Financial Model

The financial model is attached as Financial_Model.xlsx. There is a directory within the .xlsx file, an additional overview of the worksheets is listed below.

Financial_Model.xlsx

1. **Summary**
   Description of the scenarios and overview of the financial model results.
2. **Diesel**
   Calculation of the NPV for the diesel only scenario.
3. **TA S1 new trucks**
   Calculation of the NPV for trolley assist scenario 1, with the purchase of new trucks.
4. **TA S1 retrofit**
   Calculation of the NPV for trolley assist scenario 1, with retrofit trucks.
5. **TA S2 new trucks**
   Calculation of the NPV for trolley assist scenario 2, with the purchase of new trucks.
6. **TA S2 retrofit**
   Calculation of the NPV for trolley assist scenario 2, with retrofit trucks.

F

Sensitivity Analysis

The sensitivities are graphically represented in Chapter 6. In this Appendix, the original data is presented. The file Sensitivity_Analysis.xlsx is part of this Appendix, and is attached separately. There is a directory within the .xlsx file, an additional overview of the worksheets is listed below. Furthermore, a separated version of Figure 6.1 is included.

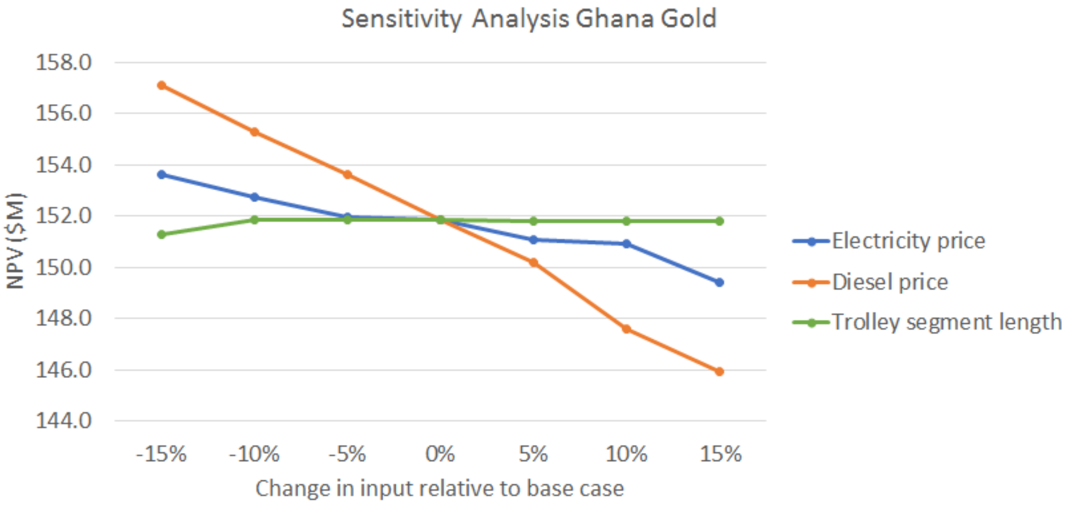
Table F.1: Numerical results from the sensitivity analysis on the six key parameters. The percentages denote the change in the parameter value, relative to the base case. All numbers are in $M.

Parameter	**-15%**	**-10%**	**-5%**	**Base Case**	**5%**	**10%**	**15%**
Electricity Price	153.6	152.7	152.0	151.8	151.1	150.9	149.4
Diesel Price	157.1	155.3	153.6	151.8	150.2	147.6	145.9
Gold Price	-19.5	71.2	76.8	151.8	165.8	228.4	290.5
Trolley Utilization	151.2	152.0	151.8	151.8	151.8	156.6	156.6
Slope Angle	-116.5	-29.8	88.6	151.8	196.8	246.1	208.7
Length of Trolley Segment	151.3	151.9	151.8	151.8	151.8	151.8	151.8

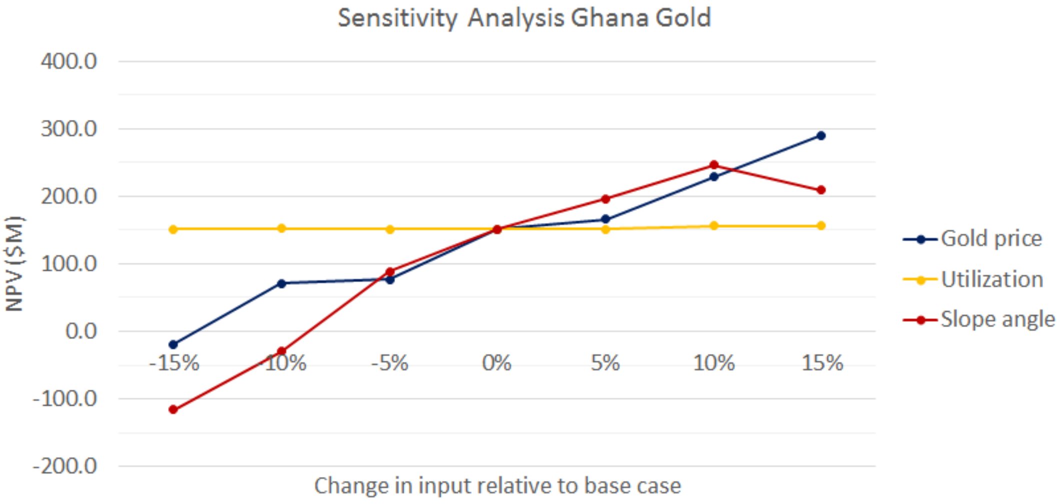
Sensitivity_Analysis.xlsx

1. **Results**
   Numerical and graphical overview of results of the sensitivity analysis.
2. **Base Case**
   Original results from the financial model, for the base case (TA Scenario 2).
3. **Diesel Price**
   Calculation of the NPV for the changed diesel prices.
4. **Electricity Price**
   Calculation of the NPV for the changed electricity prices.
5. **Au Price**
   Calculation of the NPV for the changed gold prices.
6. **Utilization**
   Calculation of the NPV for the changes in trolley utilization.

7. **Slope Angle**
   Calculation of the NPV for the changes in overall slope angle.
8. **Length Trolley Segment**
   Calculation of the NPV for the changes in length of the trolley line segment.
9. **COG**
   Calculation of the NPV for the changes in cut-off grade.



(a)



(b)

Figure F.1: Sensitivity graphs of (a) the diesel price, electricity price and length of the trolley segment and (b) the gold price, trolley utilization and overall slope angle.