Management of Mineralized Mine Waste as a Future Resource

Dylan Caverson and Eugene Ben-Awuah
Mining Optimization Laboratory (MOL)
Laurentian University, Ontario, Canada

Abstract

After mining completion, the lasting effects of mine waste from the operation are all that is left. Mine waste has negative influences on the environment, prominently due to acid-mine drainage. Currently, even though most natural resources are non-renewable, the majority of mineral resources are not mined until physical depletion, but rather current economic depletion resulting in valuable minerals left behind. With proper attention to waste management planning, the potential to increase the future profits and sustainability of the mine become available. By reprocessing the mineralized waste when metal prices fluctuate favourably, less metal will be left behind. Mineralized waste processing however has limitations. The increase in mineralized waste processability has to be assessed to be able to consider it as potential future resource. Multiple scenarios varying from conventional mining and processing practices to methods involving extensive waste management plans to prepare for future mineralized waste reprocessing are discussed in this research. The paper establishes the practicality of an effective and extensive waste management system and its benefits in life-of-mine planning particularly for non-renewable natural resources.

1. Introduction

Ever since commodities have become a form of currency, whether just for trade or for sale, the convention has been if it cannot be grown, it has to be mined. This idea has remained true, but it also has severe drawbacks, most notably the finite mineral reserves on the planet. This also leads to another issue in the mining industry, which is the convention in which mining takes place. The convention since the beginning of mining has been to mine the easiest, most profitable minerals first, leaving the either lower grade or more difficult minerals to mine for future generations. This convention will require change if the mining industry will continue to prosper.

In more recent history, reprocessing and recycling have started to come into favour, most notably on the higher grade mineralized waste of the past which requires less efficient mining activities (Lottermoser, 2011). This is the beginning of the change to stop the old convention of mining the easiest and most profitable resources first, but rather begin to physically deplete instead of just economically depleting the mineral reserves that have already been tapped into.

This paper looks to identify the issues associated with the current mining practices and waste management systems through an extensive literature review to propose a new system, perform a case study utilizing Geovia GEMS and Whittle (GEOVIA-Dassault., 2014, 2015) and discuss the results alongside any future work and recommendations. The literature review conducted for the purpose of this paper was done on two major categories. One section is regarding what needs to be addressed in today’s mining conventions. The second section focuses on the proposed changes that could be made to aid in the remedy of these scenarios. The sections are separated further in the literature review to include gold recovery, processing, resource depletion, mine sustainability and environmental impacts. A proposed framework has been established and a case study utilizing a known gold deposit will be conducted utilizing Geovia GEMS (GEOVIA-Dassault., 2014), Geovia Whittle (GEOVIA-Dassault., 2015) in tandem with the newly proposed framework to establish the potential benefits associated with a proper mineralized waste management system.

The paper is organized into six (6) sections that are all utilized in unison to convey the necessity for change in the current practices of mineralized waste management. Section 1 is the introduction; Section 2 is the literature review that was conducted; Section 3 is the proposed conceptual frameworks to be put into the case study; Section 4 is the cost and revenue forecasted data that will be coupled with the frameworks in a case study to establish the new proposed systems; Section 5 is the discussion of the results; and Section 6 is the conclusions and recommendations of the work that has been completed. This paper does not contain the case study. The case study is still currently being completed using the principals and data presented in this report alongside a set of data for a known gold deposit.

1.1. Problem definition

In mining operations around the world there is what is known as the “cut-off grade”. This is the minimum mineral content within the rock to be mined that allows the mine to operate at a profit. Currently, this means that mines will not process the mineralized rock that has been extracted with a grade lower than the “cut-off grade” and will also make attempts in design and operation to reduce the amount of rock extracted below that “cut-off grade” by leaving them in-situ.

This leads to various sustainability issues in the mining industry, led by the lack of physical depletion of the mineralized zones of rock. By only mining what is currently economical, it results in large quantities of mineralized rock left behind. For natural resources that are essentially non-renewable, this approach needs to be re-evaluated.

This research looks to evaluate different approaches to waste management with the view of considering mineralized mine waste as a future potential resource for reprocessing and implement complex systems for the management of the mineralized waste in order to use the current waste as a future resource.

1.2. Aims and objectives

The aims of this research are to improve mine sustainability by the management of mineralized mine waste and determine the impacts of mineralized waste management as a future resource through four core objectives. These objectives are:

- Analyzing and understanding the current mining and waste management practices used in the mining industry
- Proposing and implementing a conceptual framework for a waste management system that enables reprocessing of mineralized waste directly by the plant.
- Discussions and legislative recommendations for life of mine waste management systems for non-renewable natural resources.

1.3. Research and analysis methods used

In the analysis of mineralized waste management as a future resource, various techniques for evaluation are needed to confirm or refute the idea. The first technique used was a comprehensive literature review on current mining and waste management practices which are mainly based on economic depletion frameworks. Following the literature review, the research focused on using historical economic and processing data to forecast well into the future in order to examine the future aspect of the problem definition. Finally, a case study using the forecasted data and a proposed waste management strategy were simulated to establish and compare the impact of the implemented waste management systems to reprocess the mineralized waste in the future. The case study was based on a gold reserve using Geovia GEMS and Whittle (GEOVIA-Dassault., 2014, 2015).

2. Literature Review

2.1. Current mining practices

The mining industry is a vital part of the global economy as well as global technological advancements. The dependence on mining to produce large amount of both metals and non-metal to meet current needs have resulted in the processing of high volumes of mineralized materials and subsequently producing huge amount of waste (Lottermoser, 2010).

In the mining industry, not all mineralized rock is economical to extract and process under the current economic and technological conditions. This does not mean the material is worthless but can still be rich in minerals. Due to unfavourable economic conditions, processing and extraction technology limitations, full extraction of the resources from the mineralized materials may not be possible. Past processes with less efficient extraction and processing techniques have resulted in wastes with high mineral content still within them (Lottermoser, 2010).

The term "mine waste" is used to categorize the material that is extracted from the ground with no current economic value, and is thus stored or discarded rather than processed (Lottermoser, 2010). Mining operations produces large amounts of waste, be it waste rock from the extraction of mineralized rock to tailings from the processing and extraction of metals from the rock. The impoundments required to contain the waste materials often take a very large geographic footprint. These containment facilities are amongst the largest facilities used in any industry. Because of this, the long-term impacts of the waste facilities and the disposal of waste require extra attention in the design phase and in the mining operations bearing in mind that the extent of hydrological systems in waste storages are not fully understood and must be used with caution (Mining Minerals and Sustainable Development, 2002). Figure 1 is a visual representation of waste management in current mining practice. It can be seen that the waste dumps and tailings impoundments do not have a sealed base which could allow for future reprocessing of mine waste (Dold, 2008).

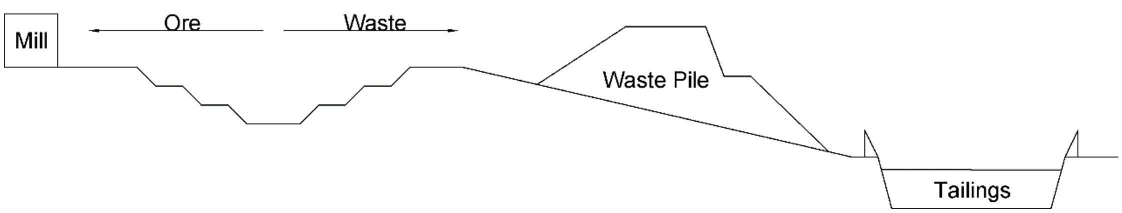

Figure 1: Current mining and processing practices scheme modified from (Dold, 2008)

In mining, technology has and still is a vital part of the industry. In order to both extract and process the minerals in the mining cycle, technology leads the way in the potential to do so. Though this is certainly the case, technology in mining evolved slowly leading up to the Industrial Revolution, at which point the need for better extraction of resources became necessity. This necessity led to the development of numerous technologies that are still essential in mining processes today, such as: flotation, new methods of pyrometallurgy, geophysics, drilling practices and machinery (Giurco et al., 2010). Improved extraction techniques and technologies have kept the relative metal prices of these metals moderately constant for over 50 years (Gordon et al., 2006). Exploration drilling technology is another major area for potential future advances. The oil industry is a major contributor in the need for faster and more efficient drilling technology. Their need for lower cost and better exploration practices drives the research in drilling technologies. 'Hot dry rock' geothermal energy production, which requires deep drilling technology to reach the hot granites at three to four kilometers below surface, has come to the forefront of energy production due to the increased drilling capabilities emanating from technological advancement. Given the need to drill deeper for future mineral discoveries and current mineral production, drilling technology advancements will continue to take a leading role in mining industry and future research prospects (Giurco et al., 2010).

The mine waste hierarchy in Figure 2 is a well-established guide for prioritizing waste management practices, showing most favoured at the top to least favoured at the bottom. As seen, minimization of creation of mine waste is of course the preferred option, whereas disposal and treatment being the least preferred option. Reuse and recycling is amongst the top feasible options in waste management (Lottermoser, 2011). However, most common practice used in conventional mining is the treatment, disposal and storage, the least favoured option.

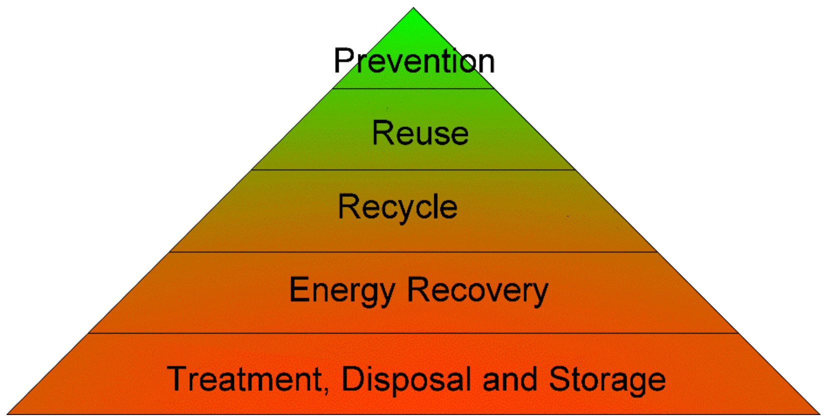

Figure 2 : Mine waste hierarchy modified from (Lottermoser, 2011)

2.2. Proposed mining practices

Not only are extraction technologies vital in mining, but the processing and refining processes are also of critical importance. This means that the future research associated with the processing and refining processes will continue to be in the forefront of the research efforts due to the declining ore grades and more complex ore compositions (easier and higher grade ores have been mined first, leaving the harder and lower grade ores behind) (Giurco et al., 2010).Technological advancements in the mining industry, processes that improve economic value of minerals (through better separation or likewise) and improved milling and refining processes will increase the potential extraction of minerals in mining operations and will prove to be essential in future processing (Hatayama et al., 2014).

In the mining industry, the waste is typically mineralized materials that are not economical to process at the time of extraction or the waste effluent that is a byproduct of the processing and refining of the materials. The economic conditions are a major contributing factor as to whether or not the material is economically viable for processing at the time of extraction. Another major factor for mineralized materials being left behind in the waste stream is processing and refining inefficiencies. These factors, amongst some others, result in the mineral reserve not reaching complete extraction, and waste streams with mineralized materials still being left behind (Lottermoser, 2010). Mine waste may not necessarily be completely worthless, but rather not economically valuable under the current economic or technological conditions. These materials often contained valuable mineralization that can be used as a future resource. As economic and technologies change, materials that were previously considered to be waste are now commodities in the new market. Furthermore, as the commodity demand and price increase, the need for the new technologies and reprocessing increases, resulting in further research efforts on the subject. Current waste can be used as a future resource in times of commodity scarcity (Lottermoser, 2011).

Figure 3 and Figure 4 show a proposed mineralized waste management system along with the mine sustainability and profits versus the life of investment graph for the corresponding system respectively (Dold, 2008).

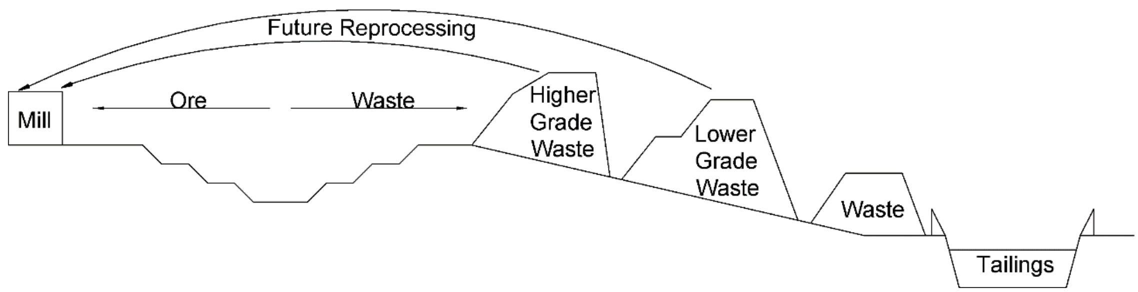

Figure 3 : Proposed waste management scheme for future reprocessing of mineralized wastes modified from (Dold, 2008)

Figure 4 is a simplified schematic of the return on investment as mine life increase due to the implementation of the waste management system as compared to the associated ore grades within the operation. This shows the additional profits for utilizing the proposed reprocessing practices and mine life, these are in addition to the profits made by utilizing the higher grade profit margins previously.

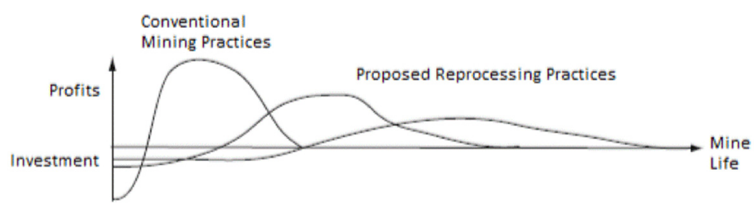

Figure 4 : Visual representation of value of proposed waste management system modified from (Dold, 2008)

The reprocessing and recycling, as well as miscellaneous reuse of the mine wastes is done for both financial return as well as the practical uses (ie. fill for roads, etc.). With the increasing demand for minerals and materials in the global market, the recovery of the valuable minerals and reuse of the wastes is becoming increasingly important and enticing (Lottermoser, 2011). Recycling and reprocessing mine wastes and effluents is done to recover the valuable minerals and metals that are leftover in the waste. This is done due to improved economic conditions or technologies in the reprocessing and refining stages, as well as potentially improved extraction methods or technologies (Lottermoser, 2011).When recycling and reprocessing mineralized wastes, the overall cost depends on various factors. The approach in modern mining has been trending toward recycling and reprocessing of mine wastes. This is becoming more possible, especially when reprocessing older mine wastes that are higher in mineralization because of improved processing and refining technologies as well as increased metal demands (Lottermoser, 2011).

Since operational decisions are often expensive to reverse, if reversible at all, it is best to make these decisions in the planning phases. These decisions range from mining method to waste management plans. This enables further decisions to have a directive, ensuring that the future decisions are supported by the intended final outcome. Mine closure plans typically only focus on the environmental aspects of closure and its impacts on the surrounding ecosystems. Integrating social and economic impacts as well is important as well to maintain sustainable mining operations (Mining Minerals and Sustainable Development, 2002).

The mining industry however is slow to change, and should focus its research on the advancement of technologies and processes that cause positive changes in the conventional mine cycles, and thus increased mine life. These advancements should not cause an increased negative social or environmental impact as a result of the mining operations as a consequence of the new technologies or practices (Prior et al., 2012).

2.3. Gold recovery and processing

As innovation continues in the mining industry, a major advancement in the gold recovery process was the implementation was heap leaching. This is done by placing the ore in large piles or "heaps" and having the solution, typically cyanide, sprayed over the piles. This causes the solution to dissolve and carry the metals from the piles of ore which can later be captured and further processed to obtain the metals. This method is now widely used in lower grade ores, most notably in gold and copper mines (Giurco et al., 2010). The recovery process in gold production is a two - staged hydrometallurgical process. The gold is first dissolved from the ore in a cyanide solution that is collected afterwards. The second stage is the recovery phase in which the gold is recovered from the solution using various techniques, typically zinc cementation or carbon adsorption (Lottermoser, 2010). Cyanide is a chemical compound used in mineral processing, typically for gold (and silver). The compound is created when carbon and nitrogen combine to form (CN^-). Cyanide is used in a process known as leaching, in which it dissolves the metals from the ore to be later recovered. This is one of the most common processed used in the mining industry to recover gold from the ores (Lottermoser, 2010).

2.4. Resource depletion

Resources that are obtained through mining are non-renewable and thus finite resources. These resources will eventually become depleted as mining operations continue and commodity needs rise. The current issue however, is the fact that reserves are not being mined to depletion in terms of the mineral resource, but rather to an economic depletion (Giurco et al., 2010). Currently, physical depletion of minerals in the mining industry does not represent a non-availability of a resource, but rather economic depletion coupled with social and environmental constraints and impacts that determine which mineral reserves are extracted (Willett, 2002; Giurco et al., 2010).

The debate of mineral depletion is not around whether or not depletion is occurring; this is well known. The debate amongst researchers is the mechanism of depletion, either physical depletion or otherwise (Gordon et al., 2006; Tilton and Lagos, 2007; Giurco et al., 2010). The debate regarding mechanisms are fueled by the question if the increase in commodity price and/or technology advancements (Giurco et al., 2010) will allow previously waste materials to be considered as resources (Willett, 2002; Prior et al., 2012). Tilton and Lagos (2007) maintain the stance that following the fixed stock paradigm is not representative of the actual availability of resources (that resources on the plant are finite); instead that an opportunity-cost paradigm is more representative of actual resource availability (usable and retrievable resource quantity with associated opportunity costs).

The "Prophesies of Scarcity" written by Williamson (1945) suggests that there is a response to the depletion of both renewable and non-renewable resources. He proposes that resource depletion models are queues that resource management should be more integral in planning phases (Giurco et al., 2010). Though this concept has mostly been researched in fields of renewable resources (fisheries, forestry, etc.), similar concepts can be discussed to some extent, with further research certainly focused on the non-renewable resources required (Giurco et al., 2010).

Based on the expectation that the mining industry will continue to advance technologically and in new techniques the efforts that were previously focused on resource depletion analysis has been hindered in the last twenty years (Giurco et al., 2010). Another issue on the horizon is the fact that as resources are becoming more available globally due to the mining industry's rapid expansion across many countries; the physical depletion of mineral resources has effectively been ignored for economical depletion instead, causing future resource considerations to be forgotten in the process (Tilton, 1996; Willett, 2002; Giurco et al., 2010). The fact that mining rates have continually increased means that eventually mineral reserves will become exhausted (Giurco et al., 2010; Prior et al., 2012).

2.5. Mine sustainability

Though progress in terms of technology and awareness as well as practices has improved in the past 30 years, the course in which correction had to be made has not been followed. Based on the rate at which resources are being consumed, the world will require more resources than available on earth in the 21st century (Meadows et al., 2005). This graph (Figure 5) shows the number of Earths required to provide the resources used by humanity and to absorb their emissions for each year since 1960, and as seen the trend continues upwards (Meadows et al., 2005). Between 1975 and 1980, humanity exceeded the capacity for the earth to sustain the activities, requiring change in practices to being to remedy the situation.

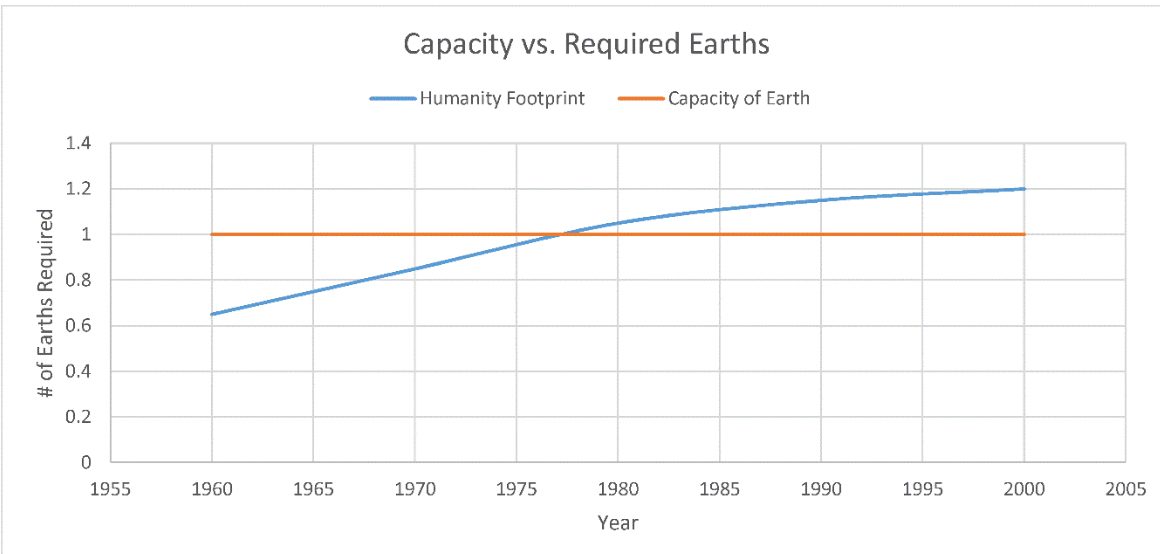

Figure 5 : footprint vs. earths required for sustainability modified from (Meadows et al., 2005)

Mineral resources will eventually become depleted within the lithosphere, leaving alternate means of production as a necessity. Since mining operations are ongoing still, a future management strategy for metal production will rise in research efforts. Physical depletion is not common in mining practices, but environmental and economic impacts cause viability of reserves to be questioned and sustainable techniques required (Prior et al., 2012).

The peak mineral phenomenon is driven by declining ore grades. This means "the concentration of a particular mineral or metal(s) being mined, as well as the quality of the ore with respect to processing (e.g. fine or coarse grained ore, mineralogy, impurities such as arsenic or mercury, etc)" (Prior et al., 2012) is declining.

In terms of sustainability it is not only the exhaustion of minerals that is of concern, but the shift from the convention of mining and processing the cheaper and higher grade ores prior to the "peak" of the reserves to the more expensive and lower grade ores after the "peak" of the reserves (Prior et al., 2012). In terms of resource sustainability, it has been argued that it is better to continue to mine from existing mines for as long as possible before opening new mines, so long that the mining operation is still operating under productive and economic viability within the sustainability dimension (Weber, 2005; Laurence, 2011).

Many issues such as land degradation and resource depletion from current unsustainable practices look to pose problems for future generations. In order to try to start remedying the situation, research into waste recycling is rising in importance (Lottermoser, 2011).

"Sustainability does not mean zero growth" (Meadows et al., 2005). This is referring to the fact that sustainable development has an interest in multiple areas of expansions, not exclusively physical expansion.

2.6. Environmental impacts

Mining requires the extraction of mineral reserves from the earth's lithosphere. This means that in order to mine the valuable materials, waste material is required to be taken out as well in the process. The goal in seeking sustainable mining operations is to minimize the waste taken out of the earth and stored in facilities (Dold, 2008). By its very nature, mining has been and will continue to be a destructive activity that leads to negative environmental impacts. The idea of sustainable mining practices and technologies is to maintain and improve extraction of metals from the ore and increase the economic benefits, while still reducing the negative environmental footprint and minimizing reclamation requirements (Dold, 2008). During mining and processing phase of mineral exploitation, the natural environment is subjected to high rate of depletion. The From production, waste rock are extracted and left in storage areas, whereas the processing and refining produces gangue known as "tailings" that is also stored in impoundments. These "waste" materials may still contain minerals that were uneconomical at the time of extract to process or leftover due to refining and processing inefficiency. This means that not all the minerals extracted from the reserve make it to the refining process, wasting some of the valuable commodities.

As a result of the above circumstance, it is very common to have large volumes of waste rock piles without an adequate records of their physical, chemical and geological properties.. These wastes can contain minerals and materials that cause adverse effects on the surrounding environment and ecosystems (Giurco et al., 2010; Prior et al., 2012).When rehabilitation is done on mining operations, which includes the issues of tailings as well as drainage (notably acid mine drainage), the rehabilitation is constrained by the available technology in both the planning and closure phases of the operation.

The rehabilitation and reclamation of mine sites involves returning the wastes (waste rock typically) to their original location (fill the voids where possible) to allow the mine site to be used for future endeavors. Similar to the mine waste hierarchy, the mine site rehabilitation hierarchy (Figure 6) is a guide for prioritizing rehabilitation strategies and planning strategies for mining operations, identifying the preferred option at the top to the least preferred at the bottom (Lottermoser, 2011).

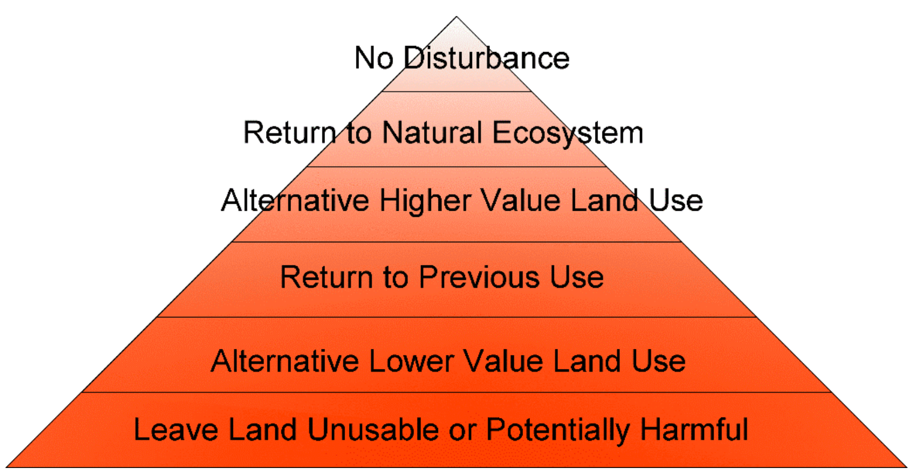

Figure 6 : Rehabilitation and reclamation hierarchy modified from (Lottermoser, 2011)

The global mining industry require companies that wish to start mining operations to undergo an environmental impact assessment prior to work being done on development of the operation. This causes the companies to identify and understand the potential environmental detriments of various aspects of the operation and allows them to attempt to minimize these activities (Lottermoser, 2010).

An example of negative impacts on the environment due to mining operations is in South Africa, the over 1100 operating mines contribute over 72% of the total solid waste stream for the country. This attributes nearly 25000 hectares of land used as waste disposal facilities, mostly in the form of tailings impoundments (Maboeta and van Rensburg, 2003; Lottermoser, 2010).

3. Conceptual Framework

By modeling various scenarios and evaluating those using real data alongside forecasted values, the argument for proper waste management systems will be made with the aim of increasing the amount of mineralized zones that reach physical depletion. The framework in Figure 7 below is used to develop the case studies for which data can be attributed and simulated to determine the practicability of such extensive waste management systems. Figure 7 also shows the impact on the mine life if reclaimable mine waste management systems is used to allow the future reprocessing of mineralized wastes.

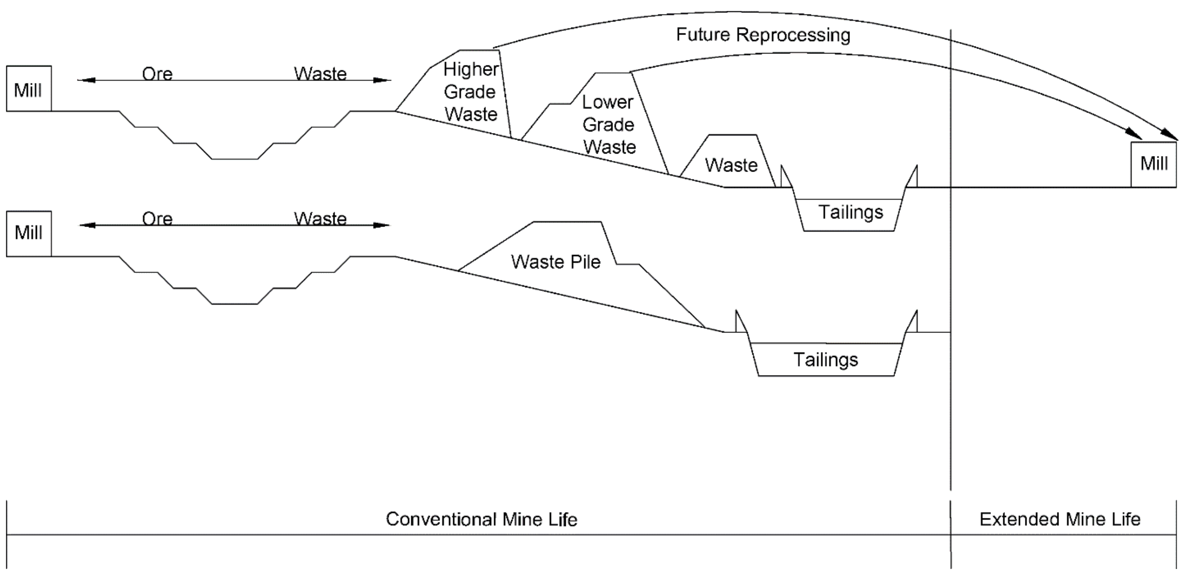

Figure 7 : Mine life impact of sustainable waste management systems

3.1. Current mining practice

The data obtained will be modeled following current mining and waste management practices which is based on economic depletion. The current price of the mineral, mining and processing cost as well as metallurgical recovery will be used in the revenue and profit calculations. This scenario will be the benchmark case in which the simulated models are compared against to establish the feasibility of the proposed waste management systems. Figure 1 shows the conventional method of mining and dealing with the waste produced from the operations based on economic depletion.

3.2. Proposed mining practices

Figure 3 shows the framework used to model three scenarios in terms of mine waste management and future reprocessing of mineralized mine wastes. The scenarios are: 1) Forecasted increased mineral price with reclaimable mineralized waste management system (economic depletion); 2) Future technology advances with reclaimable mineralized waste management system (physical depletion); and 3) combined future technology advances and forecasted increased mineral price with reclaimable mineralized waste management system.

The economic data obtained from the literature review on historical and current mining and milling practices is modeled and used as a basis for mineral price forecasting. This will be implemented using the proposed reclaimable mineralized waste management system. This system tracks the waste grades and separate the waste material into three separate stockpiles: higher grade mineralized waste, lower grade mineralized waste and complete waste (no mineralization). The initial mining operation will be done using current mineral pricing and costs as well as processing practices. These values will be used throughout the three proposed scenarios.

3.2.1. Forecasted increased mineral price with reclaimable mineralized waste management system

This model will make use of forecasted mineral price for future years, to determine whether or not it makes sense to reprocess the stockpiled mineralized rock that was previously below the “cut-off grade”. Reprocessing will incur the same costs as before with the inclusion of annual inflation, but the overall cost will be reduced due to no requirements to mine the rock. This scenario will result in an increased ore extraction due to the improved mineral economics compared to current mining practices.

3.2.2. Future technology advances with reclaimable mineralized waste management system

Using current economic data, this scenario will utilize a forecasted increase in processing technology (potential increase in the extraction of minerals from the ore) based on precedents of reprocessing of mine waste at the Mt. Morgan (Carbide Resources Ltd, 2015) mining operation, as well as others. Though this data is much more difficult to forecast than mineral prices, this scenario will utilize historical and current extraction percentages and make an assumption to which the extraction of the mineral could potentially reach. This approach will allow physical depletion and lower grade mineralized rock to be processed due to increased metallurgical recovery; which effectively lowers the “cut-off grade” and increases overall mineral extraction.

3.2.3. Combined future technology advances and increased mineral price with reclaimable mineralized waste management system

This scenario will utilize a forecasted increase in processing technology as well as a forecasted increase in mineral price. This framework will increase overall mineral extraction leading to physical depletion. With the increase in mineral prices and metallurgical recovery, it allows grades which are even lower than the two previous scenarios to be processed with increased revenue. This is the ideal case that accounts for both potential increases in metallurgical recovery and mineral prices which represents the “best case” scenario for future processing of mineralized wastes.

3.3. Forecasted revenue and cost data

From the years 1998 up to the current year (2016) the average inflation rate is relatively constant with only minor fluctuations. The data to be forecasted may use the average inflation rate compounding annually between the years considered of 1.87% (Triami Media, 2016). This value however will not be used in the forecast of the gold price since the historical data is already inflation adjusted based on the actual inflation rates per year, which will make the data very close to the average value but slightly more precise.

3.3.1. Gold price

Gold price has been forecasted based on historical data in order to determine if the reprocessing of mineralized wastes would become viable in the future. This data will be used in the case study of a known gold deposit.

Historical gold data was digitized and plotted in order to determine the basic trend in the price fluctuation in the last 50 years. The initial data was obtained online (Macrotrends, 2016). From the initial plot, a simple linear trend was first determined. If a very basic estimate of future price was to be used, the linear trend would have sufficed. However, it will not adequately represent the nature of the gold industry.

In order to forecast, a single trend was selected to represent the historic data in terms of a sinusoidal function, defining an initial amplitude and frequency. From this initial trend a simple Fourier analysis was completed with the slope being maintained along the linear trend line to try to best fit with the historic data (Fumi et al., 2013).

Fourier analysis utilizes sine waves to represent data sets and converts the trends within the set to sine waves for further analysis. It is typically done in order to analyze data with numerous harmonic frequencies, but the approach and application also applies in simple forecasting.

Figure 8 below is the graph representing the forecasted data alongside the historic data and the linear trend. Because the historic data was provided in USD, it was forecasted in the same unit. This is a simple conversion if other units are required.

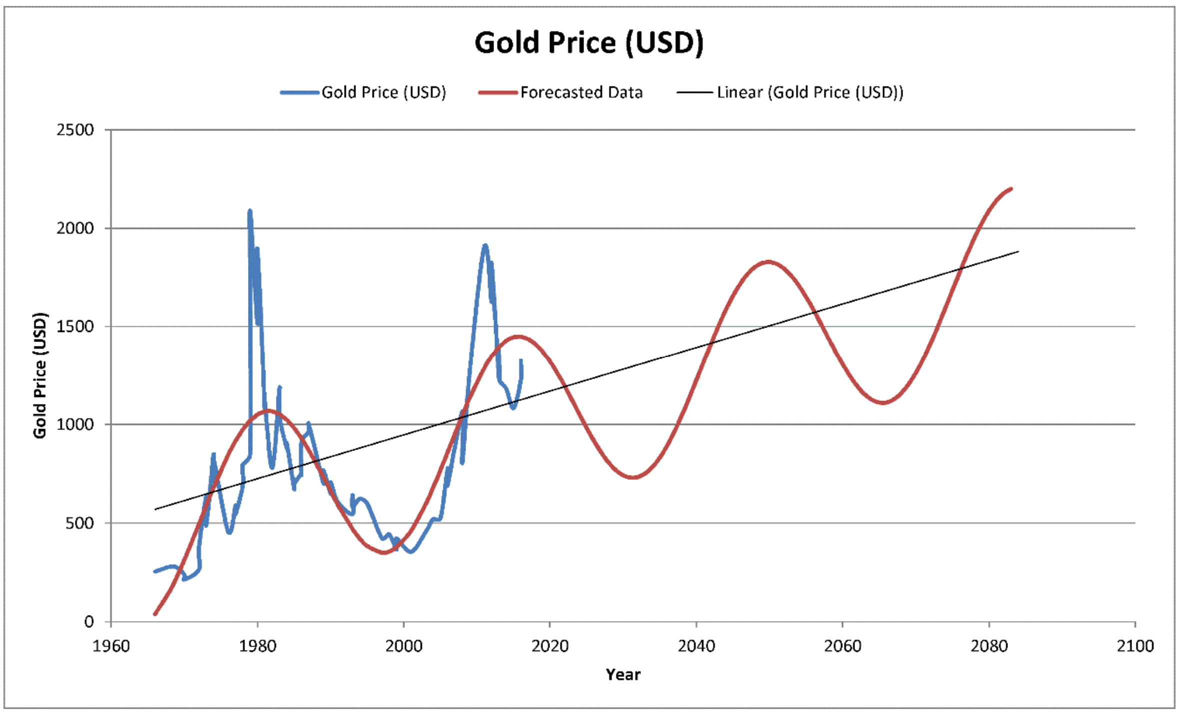

Figure 8 : Forecasted and real gold data

3.3.2. Mining costs – mining, processing, G&A and capital costs

For the purpose of this analysis, a general operating mining cost is to be used to keep a consistent economic forecast which encompasses all mining related costs. The capital and operating costs are both taken from the same source for consistency.

The data used to establish the baseline of the economic costs was taken from Argonaut Gold Pre - Feasibility Study Technical Report on the Magino Project (JDS Energy and Mining, 2016) and Detour Gold Mineral Resource and Reserve Estimate for Detour Lake Property (Detour Gold, 2016) because of the similarity between the sizes of the operations compared to the proposed case study. The estimated costs of these mines are used due to the fact that both mines are open pit gold mines operating or planned to operate in Ontario, Canada. Table 1 shows the values for operating and capital costs of the previously mentioned operation.

Table 1: Capital and operating costs from Argonaut mine and Detour Gold mine with proposed costs (Detour Gold, 2016; JDS Energy and Mining, 2016)

Capital and Operating Costs	Argonaut Costs	Detour Gold Costs	Proposed Costs
Mining Costs ($/Tonne)	8.02	2.76	5.39
Processing Costs ($/Tonne)	6.55	8.14	7.35
G&A Costs ($/Tonne)	0.7	2.47	1.59
Total Cost ($/Tonne)	15.27	13.37	14.32
Inital Capital Costs ($M)	539.8	1110	824.9
Closure Capital Costs ($M)	195.9	115	155.45
Total Capital Costs ($M)	735.7	1225	980.35

3.4. Technology – Gold recovery

The recovery in mining operations is a vital part of determining the sustainability and profitability of the mine. If the ore going into the mill is processed inefficiently then the result is precious commodity ending up in the waste stream.

To maintain consistency with other data that has been taken from industry operations, the processing efficiencies are also taken from Argonaut Gold Pre - Feasibility Study Technical Report on the Magino Project (JDS Energy and Mining, 2016). As seen in Table 2 there is certainly room for improvement in terms of recovery efficiencies, where in theory the recovery efficiencies can reach up to 99%. Table 2 shows the recovery value from the Argonaut operation as well as the value to be used in the proposed frameworks utilizing increased processing efficiencies.

Table 2: Processing efficiencies (JDS Energy and Mining, 2016)

Processing Efficiency	Argonaut	Achievable
Gold Recovery (%)	93.5	99

4. Discussion

This paper has identified a current issue in the conventional methods in the mining industry. The literature review presented has identified the major areas of concerned in the issue of waste management and exhibited not only the issues but why they exits and potential fixes to the problems. The literature also identified other sources confirming the issues being discussed and provided confirmation that the issue of waste management and mining sector sustainability is a growing and concerning danger to the future of humanity.

The conceptual framework that is presented in the paper outlines the variety of scenarios that can be both quantitatively and qualitatively analyzed to further understand the need for proper planning and waste management systems for future reprocessing of mine wastes as a resource.

The first framework that can be analyzed and quantitatively investigated is the conventional mining techniques framework. This framework involves utilizing the cut-off grade to determine which ore is mined and sent to the processing facilities and which rock that is extracted and piled in a waste pile. Though this seems like a reasonable way to perform mining as it is the common practice, it does not address the issue of the waste still containing valuable mineralization in the stream. Another issue that this convention does not address is the fact that mining only occurs until economic depletion rather than to physical depletion. Utilizing this convention leaves behind resources in the ground that have not even been extracted, effectively reducing the overall mineral reserve and global minerals available.

Once the convention mining practices have been investigated, the proposed framework can begin investigation. It is broken into three separate scenarios in which each scenario will be analyzed to emphasize the importance of a proper waste management system. All scenarios in the framework can be analyzed both quantitatively and qualitatively to assess the feasibility and importance of the system.

The first scenario in the proposed framework considers an increase in the mineral price in which one mechanism of the reprocessing feasibility is met. By implementing a waste management system in which the mineral content or grade of the waste is tracked and the waste is properly sorted to allow for the reprocessing to occur in a manner that the most profitable mineralized materials can be processed first. Best practice would be to separate the "highest grade mineralized waste" from the "lowest grade mineralized waste" and subsequently from the material that contains no mineralization. Processing the "highest grade mineralized waste" first and working down to the "lowest grade mineralized waste" is done because the gold industry has a very volatile economic history, causes large fluctuations in the gold price. By ensuring the profitable materials get processed in the time that they are profitable is essential to the effectiveness of the waste management strategy.

The second scenario in the proposed framework considers the technological advances that may occur in the processing and refining technologies while keeping the gold price constant for the sake of this scenario. From Table 2 in this report, the refining efficiency is typically in the range of 93% to 94%, with this scenario considering a practical value of approximately 93.5% (JDS Energy and Mining, 2016). This leaves the maximum potential for the efficiency to increase by 6.5%, though a more practical and achievable increase of up to 5.5%. The other consideration in this scenario is the reduction in processing cost with the increase in processing technology. Though the maximum potential benefit from this scenario in terms of monetary value may not have the same impact as in scenario one of the proposed framework, which has effectively an infinite ceiling, the stability of these benefits are more constant and much more sustainable. This scenario utilizes the same principles as in the previous scenario; with the major difference in this being that any of the profitable ores can be processed once the new technology is in place due to constant gold price, though from a net present value standpoint the highest grade should be done first. Another notable improvement this scenario presents is the potential for a greater percentage of physical depletion of the reserve due to the ability to process and refine more of the mineralization from the materials.

The final scenario in the proposed framework considers both the increase in gold price as well as the technological advances in the processing and refining technologies simultaneously. This scenario seeks to combine what the likely scenarios that will be seen in the future of the industry will hold. Based on the increase in gold price coupled with the increased processing efficiencies, this scenario will provide the greatest benefit in both monetary value as well as physical resource depletion. The scenario uses the same concepts as the previous two, but combining some of the aspects. The processing of the mineralized waste should follow the pattern outlined in the first scenario of the proposed framework, processing the "highest grade mineralized waste" first and working down until the processing is no longer economical. With the combined scenarios the processing will be able to occur earlier in the gold price increase due to the efficiency increase, and will be able to process lower grades than either separately due to the combined positive mechanics.

5. Conclusions and Recommendations

This paper put forth a proposed framework in which the conventional methods in the mining industry are challenged to change in order to provide a sustainable future for the industry, particularly due to the depletion of non-renewable natural resources. By establishing a framework in which waste management is at the forefront of the design of the operation it helps to create a more sustainable operation while promoting the physical depletion of the resources available on earth rather than just the economic depletion of the resources. By utilizing proper waste management systems, it is suggested that the mineralized waste stream can be reprocessed in the future and considered a future resource rather than waste. Though the case study is not completed in this report, this paper presents the methodology in which the investigation will be approached and carried out in order to quantify the impacts of an extensive mine waste management system that allow the waste from the operation to be utilized as a future resource.

In order for the mining industry to continue to meet the rising metal demands, sustainable management of resources is essential. Increase in potential technologies as well as positively trending gold prices will allow for further physical depletion of both new and old mineral reserves. Both the qualitative assessment coupled with the future quantitative investigation will seek to put forth a new framework for the mining and mineral industry to consider in the planning phases to ensure sustainable mining continues into the future. It is also recommended that legislative changes be made for all mineralized waste to be properly stored and documented.

6. References

[1] Carbide Resources Ltd (2015). Mount Morgan PFS Confirms Potential for Low Cost Operation. ASX/Media Announcement

[2] Detour Gold. (2016). Mineral Resource and Reserve Estimate for Detour Lake Property NI 43-101.

[3] Dold, B. (2008). Sustainability in metal mining: From exploration, over processing to mine waste management. *Reviews in Environmental Science and Bio/Technology*, *7* (4), 275-285.

[4] Fumi, A., Pepe, A., Scarabotti, L., and Schiraldi, M. (2013). Fourier Analysis for Demand Forecasting in a Fashion Company. *International Journal of Engineering Business Management*, (Special Issue on Innovation in Fashion Industry),

[5] GEOVIA-Dassault. (2014). GEOVIA GEMS. Ver. 6.5, Vancouver, BC, Canada.

[6] GEOVIA-Dassault. (2015). GEOVIA Whittle. Ver. 4.5, Vancouver, BC, Canada.

[7] Giurco, D., Prior, T., Mudd, G. M., Mason, L., and Behrisch, J. (2010). Peak Minerals in Australia: A Review of Changing Impacts and Benefits.

[8] Gordon, R. B., Bertram, M., and Graedel, T. E. (2006). Metal stocks and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *103* (5), 1209-1214.

[9] Hatayama, H., Tahara, K., and Daigo, I. (2014). Worth of metal gleaning in mining and recycling for mineral conservation. *Minerals Engineering*, *76* 58-64.

[10] JDS Energy and Mining (2016). Pre - Feasibility Study Technical Report on the Magino Project NI 43-101. paper Document Number,

[11] Laurence, D. (2011). Establishing a sustainable mining operation: An overview. *Journal of Clean Production*, *19* (2-3), 278-284.

[12] Lottermoser, B. G. (2010). *Mine Wastes: Characterization, Treatment And Environmental Impacts.* Springer, Berlin, Germany,

[13] Lottermoser, B. G. (2011). Recycling, reuse and rehabilitation of mine wastes. *Elements*, *7* (6), 405-410.

[14] Maboeta, M. S. and van Rensburg, L. (2003). Bioconversion of sewage sludge and industrially produced woodchips. *Water, Air & Soil Pollution*, *150* (1), 219-233.

[15] Macrotrends, L. L. C. (2016). Gold Price - 100 Year Historical Chart. Retrieved 2016/04/22/, from: http://www.macrotrends.net/1333/historical-gold-prices-100-year-chart

[16] Meadows, D., Randers, J., and Meadows, D. (2005). *Limits to Growth: The 30 Year Update.* Earthscan, London, UK,

[17] Mining Minerals and Sustainable Development (2002). *Breaking new ground: Mining, Minerals and Sustainable Development project.* Earthscan, London, UK,

[18] Ontario Ministry of Northern Development of Mines (2016). The Mining Act. Retrieved 2016/09/06/, from: http://www.mndm.gov.on.ca/en/mines-and-minerals/mining-act

[19] Prior, T., Giurco, D., Mudd, G. M., Mason, L., and Behrisch, J. (2012). Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change*, *22* (3), 577-587.

[20] Tilton, J. E. (1996). Exhaustible resources and sustainable development: Two Different Paradigms. *Resources Policy*, *22* (1-2), 91-97.

[21] Tilton, J. E. and Lagos, G. (2007). Assessing the long-run availability of copper. *Resources Policy*, *32* (1-2), 19-23.

[22] Triami Media, B. V. (2016). CPI Canadian Inflation. Retrieved 2016/09/06/, from: http://www.inflation.eu/inflation-rates/canada/historic-inflation/cpi-inflation-canada.aspx

[23] Weber, I. (2005). Actualizing Sustainable Mining: Whole Mine, Whole Community, Whole Planet through Industrial Ecology and Community-Based Strategies. Weber Sustainability Consulting

[24] Willett, K. (2002). Managing Australian Mineral Wealth for Sustainable Economic Development. International Institute for Environment and Development

[25] Williamson, H. F. (1945). Prophecies of Scarcity or Exhaustion of Natural Resources in the United States. *The American Economic Review*, *35* (2), 97-109.