Strategic Evaluation of Mineralized Waste Rocks as Future Resource

Bright Oppong Afum, Dylan Caverson and Eugene Ben-Awuah
Mining Optimization Laboratory (MOL)
Laurentian University, Sudbury, Canada

ABSTRACT

Current mining practices do not extract all mineralized rocks due to the present mine planning concept of economic resource depletion as opposed to physical resource depletion. Improvement in factors including mineral prices and processing recovery could potentially make mineralized waste rocks profitable. This paper discusses the management of mineralized waste rocks as future resource, and further proposes a framework that maximizes the benefits of mining and processing mineralized waste rocks. A gold deposit was used as case study to evaluate the conventional and proposed waste rock management practices. Future gold prices were modeled using Fourier analysis while technological advancement in gold processing recovery were deduced from historical and current trends. The evaluation was based on the net present value (NPV), life of mine (LoM), internal rate of return (IRR), cashflow, resource depletion ratios and payback periods. The potential simultaneous increase in future gold prices and processing recovery (Scenario 3) was the option with the best performance. Implementation of Scenario 3 will deplete the mineral resource by 92.3%, compared to 59.5% depletion ratio by the conventional practice. The estimated NPV and LoM of Scenario 3 increased by 12.6% and 82.9% respectively, compared to the conventional practice. A well-integrated mining strategy that focuses on both economic and physical resource depletion is vital to the management of mineral resources for economic, social and governmental benefits of a country. Policy and technical reforms have been recommended to encourage mining companies to consider the proposed mineralized waste rocks management framework in their long term strategic mine plans.

1. Introduction

As mineral commodities have become a form of currency, whether for trade or sale in this growing technological and industrial economy, the need and value for metals and minerals have significantly increased. The dependence on mining to produce large amounts of these minerals to meet current needs have resulted in the processing of high volumes of mineralized material and subsequently producing huge amounts of waste rocks and processing plant tailings (Lottermoser, 2010). Thus, the convention, "if it cannot be grown, it has to be mined", will have severe notable drawbacks mostly because of the depleting nature of finite mineral resources on the planet leading to sustainability challenges on the management of mineral resources.

In the mining industry, not all mineralized rock is profitable for extraction and subsequent processing under the current economic regime, available processing techniques and technological constraints. Lottermoser (2010) noted that, extraction and processing techniques used in the past were less efficient, and resulted in mine wastes of significantly high mineral contents. The term "mine waste" is used to categorize the material that is extracted from the ground with no current

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economic value, and is thus stored or discarded rather than processed. Similarly, "mineralized mine waste" refers to the category of rock material containing some percentage quantities of mineral content with future potential economic benefits. In their current form, mineralized waste rocks are not profitable based on current economics, available processing techniques, technological constraints and governmental policies.

In recent times, mining of material previously defined as waste for older mines is very common. These mining operations require less energy in extraction and transportation for reprocessing and/or recycling (Lottermoser, 2011). It is interesting to note that, the traditional mining and waste rock management practices do not accommodate the concept where waste material potentially become mineral resources for future generations. The traditional mining model where the easiest, most profitable minerals are mined first, leaving the lower grades or difficult-to-process materials in-situ or transported to waste dumps needs to be modified. The changes will promote the sustainability of the mining industry and create opportunities to harness the full benefit of the mineral resources. For natural resources that are essentially non-renewable, the conventional mining approach needs to be re-evaluated. This will be the beginning of the revolution to the old convention of mining where economic depletion of mineral resources is preferred to physical depletion.

This paper evaluates the current traditional mining and waste rock management system, and further proposes an innovative approach for mining and waste rock management that considers mineralized waste rock as potential future mineral resource. Using GEOVIA GEMS and Whittle software (GEOVIA-Dassault, 2015, 2014), a conceptual framework for mine waste management system that ensures future processing of mineralized waste rock has been evaluated with real data from two mining companies in Canada. The results of the study together with legislative requirements have been discussed. Recommendations on resource policy reforms and modifications to the management of mine waste rocks as a potential future resource have been proposed.

1.1. Mineral resource depletion

Current general mining practices aim at maximizing the net present value for the operation by mining the easier to access and higher grade minerals first while leaving the more difficult and lower grade minerals in-situ or sent to waste dumps. Mineralized waste rocks are mined to uncover the ore blocks underlying such waste rocks. These mineralized waste rocks are sent to waste dumps which end up mixing with the non-mineralized waste rocks. This conventional waste rock management method results in the loss of future potential mineral resource and sustainability issues due to the progressive peak mineral requirement paradigm and growing mineral consumption. Sustainability refers to the continuous development in areas including physical expansion, social, environmental and economic development of mineral resources. However, unsustainable practices lead to numerous challenges such as land degradation and resource depletion. Mineral resource depletion has been a concern for most researchers in resource sustainability (Gordon et al., 2006; Tilton and Lagos, 2007; Giurco et al., 2010). Discussions about the mechanism of resource depletion have deepened with researchers finding solutions to questions such as "will previously categorized waste rock materials be mined when commodity prices increases and/or mining technology advances?" (Willett, 2002; Giurco et al., 2010; Prior et al., 2012). Tilton and Lagos (2007) however maintained that the fixed stock paradigm is not representative of the actual availability of resources but instead, an opportunity-cost paradigm is more representative of actual resource availability.

In terms of resource sustainability, it has been argued that it is better to continuously prolong the extraction of existing mines than opening newer mines as long as the mining operation is still productive and economic within sustainability dimensions (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 remedy the situation, research into waste recycling is rising in importance (Lottermoser, 2011), and the concept "sustainability does not mean zero growth" (Meadows et al.) is gradually being advocated.

The "Prophesies of Scarcity" suggests that there is a response to the depletion of both renewable and non-renewable resources (Williamson, 1945). Giurco et al. (2010) proposed that resource depletion models are indications that resource management should be more integrated in the planning phases. Although resource management concepts have mostly been researched in fields of renewable resources such as fisheries and forestry, it has barely been discussed as a critical concept in the fields of non-renewable resources. Efforts that were previously focused on non-renewable resource depletion analysis have been hindered in the last two decades (Giurco et al., 2010). Due to the expansion of the mining industry resulting from discoveries of several large mineral resources, advances in processing technology, better techniques of mining and increases in commodity prices; focusing on the concept of physical depletion as opposed to economic depletion of mineral resources must be strategic.

In recent times, discussions on resource governance and how nations can maximize resource benefits have increased. For instance, the Alberta Energy Regulator (AER) has established criteria that define the mining cut-off grade and minimum processing plant recovery factor. According to Directive 082 by the AER (Ellis, 2016), the criteria seek to ensure conservation and further prevent sterilization of oil sands resources in the Province of Alberta, Canada. The criteria outline that:

a) The in-situ oil sands cut-off grade, defined as the minimum bitumen content of oil sands ore, must be 7 weights per cent bitumen; and

b) The processing plant recovery is a variable factor based on the average bitumen content of the as-mined ore. The factor is determined as follows:

   − If the average bitumen content of the as-mined ore is 11 weights per cent bitumen or greater, the recovery factor is 90 weights per cent.

   − If the average bitumen content of the as-mined ore is less than 11 weights per cent bitumen, recovery is determined by Equation (1), where x is the average weight per cent bitumen content of the as-mined ore:

$$\text{Recovery} = -202.7 + 54.1(x) - 2.5(x^2) \tag{1}$$

1.2. Large volume waste management

In the mining industry, development of essential technologies including flotation, new methods of pyrometallurgy, geophysics, drilling practices and machinery have improved the extraction techniques and technologies over the past 50 years (Gordon et al., 2006). Large volume waste often refers to waste rock and/or tailings generated during the mining and processing operations of a typical mine. The mine waste management hierarchy in Fig. 1 is a well-established guide for prioritizing waste management practices, showing most favored approach at the top to least favored approach at the bottom. As presented in Fig. 1, minimization of mine waste is the most preferred option, whereas treatment, disposal and storage are the least preferred options. Reuse and recycling is amongst the top feasible options in waste management (Lottermoser, 2011). However, the most common practice used in conventional mining and waste management is the treatment, disposal and storage options.

Technological advancements in the mining industry potentially improve the economic value of mineral deposits. These advancements lead to efficiencies in milling and refining processes that invariably increases the potential extraction of minerals in mining operations (Hatayama et al., 2014). Mineralized mine waste may not necessarily be completely worthless, but rather not profitable under the current economic or technological conditions. These materials often contain valuable mineralization that can be potentially extracted in the future. As extraction economics and technologies improve, materials that were previously considered waste can be processed. Furthermore, as commodity demand and price increases, the need for innovative technologies and reprocessing will also increase. This will result in further research efforts on these subjects.

The recycling and processing, as well as miscellaneous reuse of mine wastes (such as fill for roads, reclamations, etc.) are done for both financial return as well as convenience. With the increasing demand for minerals and materials in the global market, the recovery of valuable minerals and reuse of waste rock materials are becoming increasingly important and enticing (Lottermoser, 2011). In the past, gold recovery efficiencies were in the ranges of 35% to 60%, depending on the ore properties and extraction techniques (Eissler, 1896). Based on recent technological advances in recovery techniques, most previously abandoned mineralized mine waste are potential resources for reprocessing.

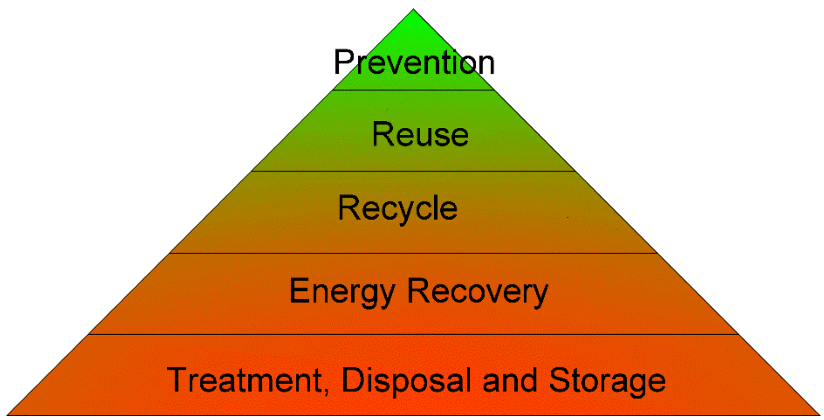

Fig. 1: Mine waste management hierarchy modified after Lottermoser (2011)

1.3. Current mining and waste management practices

Waste in mining is categorized as rock materials that are not economical to process at the time of extraction or the byproduct effluent from the processing and refining of ore materials usually deposited at the tailings impoundment. These waste dumps or containment facilities often require very large geographic footprint for their management. Because of this, the long-term impacts of these waste facilities require extra attention during the design and mining phase bearing in mind that the extent of hydrological systems in waste storages are not fully understood (Mining, Minerals and Sustainable Development (MMSD), 2002). Fig. 2 is a representation of waste management in current mining practices.

It can be seen that the waste dumps and tailings impoundments are not usually considered to have opportunities for future reprocessing as part of the long term waste management of the mine (Dold, 2008). Typical mining companies transport any rock material containing minerals below the cut-off grade to the waste dumps. Thus, non-mineralized and mineralized waste rock materials containing minerals lower than the cut-off grade but required to be mined to gain access to blocks of higher grades are dumped together on the waste pad. Occasionally, these mineralized and non-mineralized waste rocks are used to backfill voids or valleys, for road and civil constructions, and as backfill materials during pit reclamation.

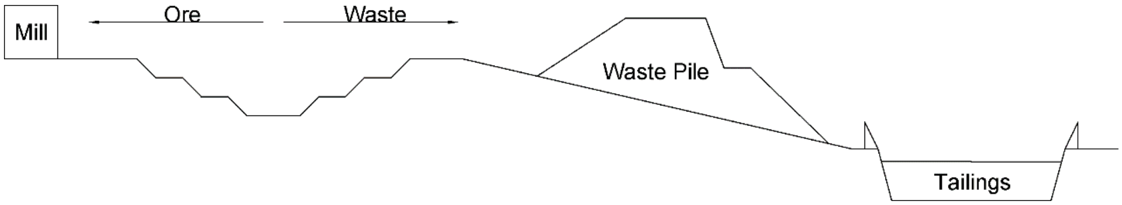

Fig. 2: Current mining and processing scheme modified after Dold (2008)

A typical mining company such as Sankofa Gold Limited in Ghana currently mines and processes the low grade materials (tailings and mine waste rock) of the former Prestea Goldfields Ltd – a previously active underground mine (Gbireh et al., 2007). After several years of closure of this underground mine, it has been reopened and is being operated by Golden Star Resources, Prestea Mines (Zhang et al., 2015; Brakopowers, 2016). Perseus Mining (Ghana) Limited has fully explored and is currently mining an abandoned old mining pit that was backfilled by AngloGold Company Limited several years ago (Amegbey et al., 2016). AngloGold Ashanti Obuasi Mine has completed the re-mining of its Diawuso tailings in 2015 (AngloGoldAshanti, 2015). Such reopening of old mines and re-mining of mineralized waste rocks was not managed as potential future mineral resource. The Mount Morgan mining operations (Carbide Resources, 2015), is also another gold and copper mine located in Queensland, Australia, that is being reworked after several years of abandoning of the mining site.

These historical information supports the fact that, if mine management had potentially mined the mineralized waste rocks and stockpiled them for the future, there would have been maximum exploitation and recovery of the existing mineral resources of that region. Furthermore, current environmental and social impacts of these abandoned mineralized waste rock and the preparation of these abandoned mines for mining in their current form would be avoided.

1.4. Proposed mining and waste management practices

Based on the rate at which resources are being consumed, the world will require more resources than available on Earth in this century (Meadows et al., 2005). Fig. 3 shows the continuous upward trend in the number of Earths required to provide the needed resources for man's use and to absorb the associated emissions per year since 1960. Between 1975 and 1980, humanity exceeded the capacity of the earth to sustain our current activities, requiring change in practices to remedy the situation.

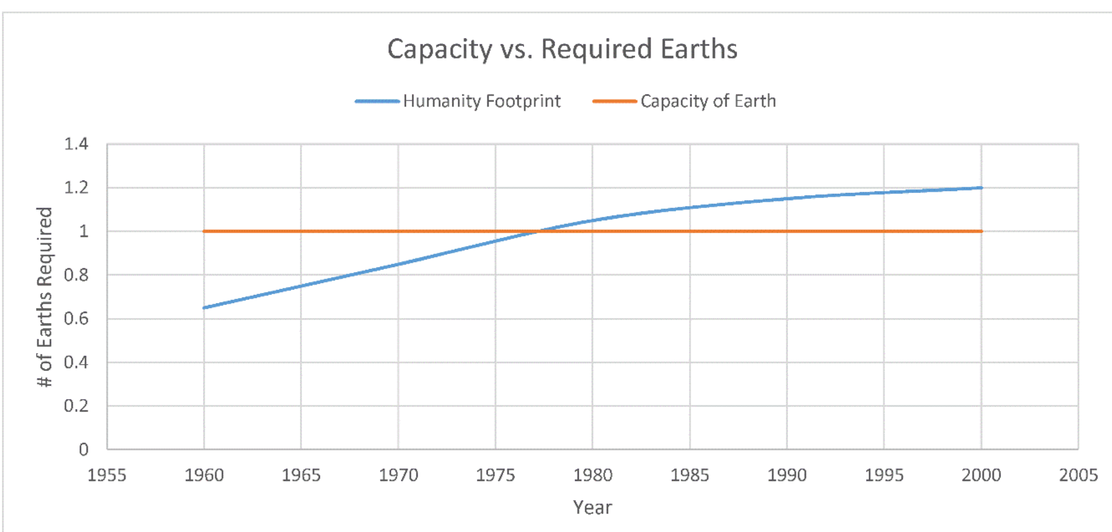

Fig. 3: Footprint vs. earths required for sustainability modified after Meadows et al. (2005)

Current mineralized waste rocks can be used as a future resource in times of commodity scarcity (Lottermoser, 2011), technological advancement and, improvements to mining and processing techniques. Managing the mineralized waste rock as future resource, coupled with existing environmental consciousness will reduce the mining footprint and negative social impacts. Fig. 4 shows the proposed mining and mineralized waste management framework modelled after (Dold, 2008). Due to favorable conditions of possible commodity price increase and/or cost reduction, as well as technological advancement to increase recoveries in the future, the potential return on investment and mine life increases. Fig. 5 shows a simplified schematic of the return on investment as mine life increases due to the implementation of the proposed system. This shows the profit profiles and extension of mine life compared to the conventional mining system.

The basic concept of the proposed framework is to ensure that as much as possible, the existing mineral resources are physically depleted as opposed to economic depletion. Fig. 6 shows the conceptual framework used to model the various mining and waste management scenarios that allow for future reprocessing of mineralized waste rocks compared to existing conventional practice. The framework is used as a basis to develop and simulate with mine data, two case studies to determine the feasibility of the proposed extensive mining and waste management system.

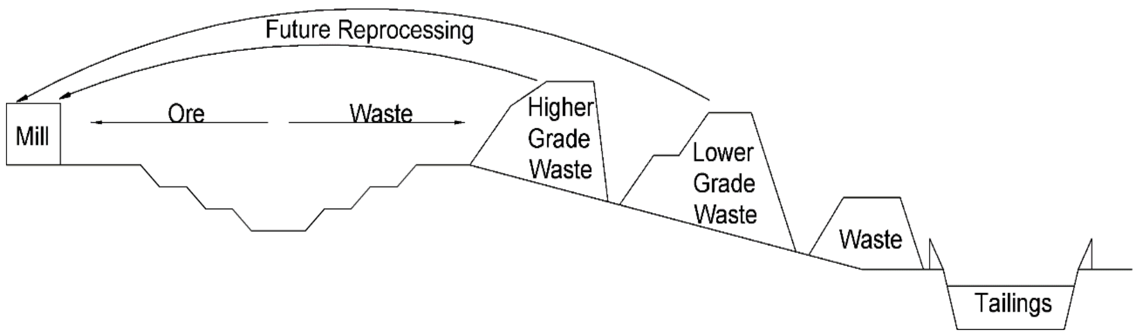

Fig. 4: Proposed waste management scheme for future reprocessing of mineralized wastes modified after Dold (2008)

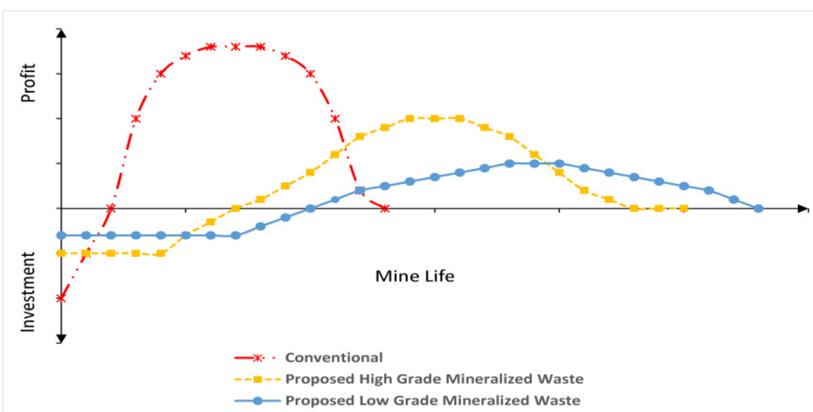

Fig. 5: Visual representation of value of proposed waste management system modified after Dold (2008)

Case Study 1 highlights the conventional mining practice with current mineral price and processing technology as exist in most mining operations today. Case Study 2 depicts the proposed mining and waste management practice which features future mineral price increase and processing technology advancements for an extended mining operation. For simplification, it was assumed in Case Study 2 that all other future mining economics data remain the same.

Using the current and forecasted economic, mining and processing data for similar gold mines in Canada, three scenarios of the proposed framework (Case Study 2) were evaluated and compared to the results of the conventional mining practice (Case Study 1). These scenarios were based on:

1) future increase in mineral price; 2) future technological advancement; and 3) future technological advancement and increase in mineral price. The comparison was made on the estimated total revenue, overall life of mine, internal rate of return (IRR) and payback period; while ensuring physical depletion of the mineral resources to promote sustainable mining.

Due to a potential increase in future price of the mineral, the first scenario evaluates the feasibility of mining and processing mineralized waste rock previously categorized as materials below the established "cut-off grade" per the current economic conditions. The second scenario evaluates the feasibility of mining and processing mineralized waste rock based on the effect of future technological advancement in processing (thus, processing recovery improvement) of the mineralized waste rock. The third scenario evaluates the economic potentials of mining and reprocessing mineralized waste rock in the future when both processing technology advances and mineral prices increase in the future. This third scenario is the "best case" scenario for future mining and processing of mineralized wastes.

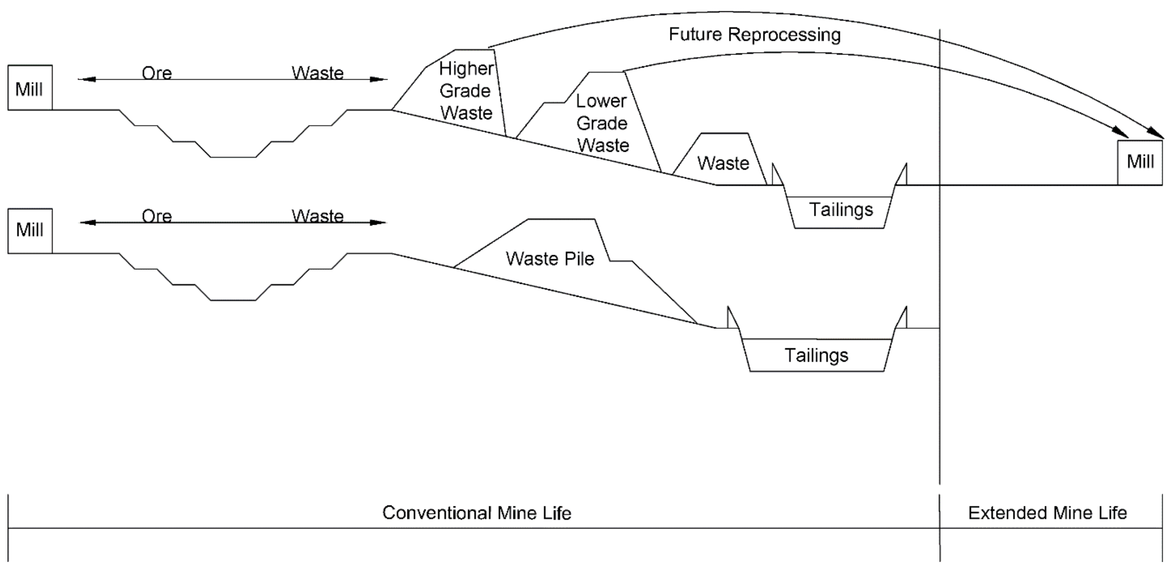

Fig. 6: Mine life impact of sustainable waste management systems

2. Quantitative evaluation

2.1. Brief description of orebody

The gold (Au) deposit in the case study is very shallow and uniform with an average grade of 1.73 g/t and spans an approximate area of 1.0 km^2. The mineral resource was estimated in GEOVIA GEMS 6.7.3 and contains a total of 98.7 Mt of mineralized rock. With a cut-off grade of 0.5 g/t, 76.2 Mt of mineralized rock at an average grade of 1.8g/t was categorized as ore while 20.5 Mt of the resource with an average grade of 0.28 g/t was categorized as mineralized waste. Using the economic data provided in Table 1, the optimum pit was generated with GEOVIA WHITTLE 4.6 (GEOVIA-Dassault, 2015).

2.2. Current economic data

Current economic data on mining and milling operations were garnered and used as basis for the evaluation of the current conventional mining and waste management practices, and the three scenarios of the proposed mining and waste management framework. These economic data were averaged from two Canadian open pit gold mines feasibility reports. The data include mining and processing costs, general and administrative costs and, capital and closure costs. The current Au price used for the evaluation is C$ 1,600 (USD$ 1,165). The current economic data including the estimated operating and capital costs are presented in Table 1.

Table 1: Average capital and operating costs from two open pit gold mines in Canada

Capital and Operating Costs	Values
Mining Costs (C$/tonne)	5.39
Processing Costs (C$/tonne)	8.93
G&A Costs (C$/tonne)	1.59
Selling Cost (C$/Oz)	53.57
Re-handling Cost (C$/tonne)	0.50
Total Cost (C$/tonne)	16.45
Initial Capital Costs (C$M)	740.00
Closure Capital Costs (C$M)	250.00
Total Capital Costs (C$M)	980.35

2.3. Mineral price forecast data

Historically, gold price has remained fairly constant over a century from 1833 to 1968 before it started to fluctuate (Macrotrends, 2016). A 50-year historical data on gold price from 1966 to 2016 (Macrotrends, 2016) was used in generating a model for predicting future gold prices. Future gold prices have been modeled by researchers based on several factors including gold demand and supply dynamics, oil prices, international inflation, devaluation of the US dollar versus other currencies, prosperity of world economics and international political environment. Some of the tools and techniques used to model the future prices of gold include simple statistical approach, application of neural networks, diffusion models, nonlinear models, time-series forecasting methods and inferences (Grudnitski and Osburn, 1993; Hadavandi et al., 2010; Shafee and Topal, 2010; Fumi et al., 2013; Makridou et al., 2013; Li, 2014).

Using the 50-year historic data, a single trend Fourier analysis based on (Fumi et al., 2013) was followed to model the next 50-year future gold price. Fig. 7 shows the plot of the historical gold prices and the forecast for the next 50-year future gold price. The average inflation rate compounded annually for the past 20 years was estimated as 1.87% (Triami Media, 2016). This value was however not used in the forecasting of the gold price since the historical data is already inflation-adjusted based on the actual year-on-year inflation rates. This ensured the forecast data were more precise and very close to the average trend value. An estimated future gold price of C$ 2,400 (USD$ 1,777) per ounce was used for the evaluation of the proposed framework. This corresponds to future mining in the year 2050; which is the next expected large-scale trend gold mining boom beyond 2017.

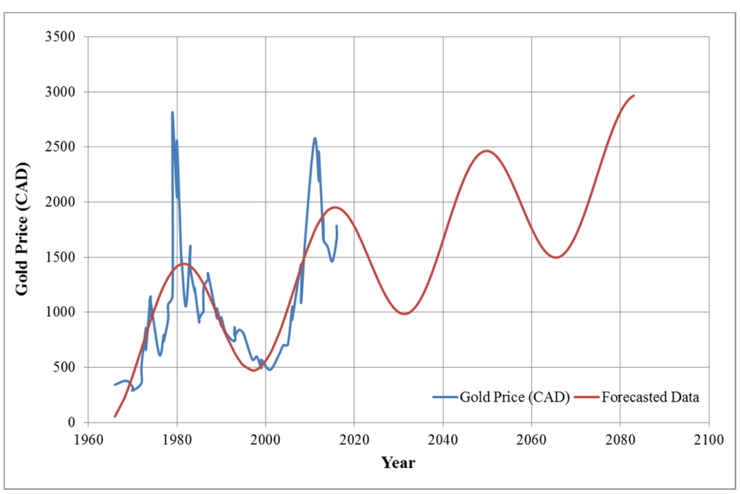

Fig. 7: Historical and forecasted gold price trends

2.4. Processing recovery forecast data

The estimated gold recovery per the feasibility reports of the two open pit gold mines are 93.5% and 92.5%. However, an estimated average gold recovery of 93% was used for the evaluation of the conventional framework. Currently, gold mining companies such as the Tarkwa Mine of Goldfields Ghana Limited and South Deep Gold Mine of Goldfields South African Limited are able to respectively achieve average processing recoveries of 96.5% and 97% (Goldfields, 2016). Based on historical gold recovery performance (Eissler, 1896; Mitchell et al., 1997), and current gold processing recoveries, the future gold processing recovery efficiency used for the proposed framework was forecasted to be 99%.

2.5. Comparative evaluation of the mining and waste management systems

Waste rock management based on the current conventional waste management system and the three scenarios of the proposed waste management options were evaluated using current and future economic, technical and processing parameters as discussed in Section 2. A run-of-mine (RoM) pad with a minimum Au grade of 0.50 g/t was created while a mineralized waste stockpile with a minimum Au grade of 0.01 g/t was also created for the evaluations. A discount rate of 10% was applied during the period when the mine is exploited per the conventional waste management system. After this period, a discount rate of 8% was applied until the remaining orebody was mined out. Applying a discount rate of 8% after the conventional mine life is due to a reduction in the associated risk of the project since more information in relation to the orebody characteristics is well understood. The processing capacity of the plant was 4.2 Mt/year and the mining capacity was 20 Mt/year. For this research, the mining recovery fraction and the mining dilution fraction were each set to 1.0 for the case studies.

3. Results and Discussions

The conventional practice of waste management was evaluated and the results compared to the results from the three scenarios of the proposed framework namely: Scenario 1 - future gold price increase; Scenario 2 - future processing recovery advancement; and Scenario 3 - future increase in gold price and processing recovery advancement. The results are summarized in Table 2.

Fig. 8 shows a comparison of the NPV computed for the conventional practice and the three proposed waste management options. The NPV of Scenarios 1 and 2 were lower than the NPV of the conventional practice. The NPV of the proposed waste management system in Scenario 3 (C$ 427.6 M) increased by 12.6% compared to the NPV of the conventional waste management practice (C$ 379.9 M).

The comparison indicates that, the combined effect of future increase in gold price and technological advancement (processing recovery), Scenario 3, was the option with the best performance. With a total ore resource of 98.7 Mt, Scenario 3 depleted 91.1 Mt of ore, constituting about 92.3% of the entire resource. This indicates that 7.7% of the mineralized material (7.6 Mt) is left unmined. The quantity of mined and processed mineralized material per the conventional waste management practice is 58.8 Mt, constituting about 59.5% of the existing total resource. The current waste management practice which is based on the concept of economic depletion will leave about 40.4% of the mineralized material behind. The proposed waste management framework ensured a mineral resource depletion ratio increase from 59.5% to 92.3%.

The cumulative cashflow for the three proposed scenarios and the conventional practice is shown in Fig. 9. The drop in the cashflow for both Scenarios 1 and 3 at the 17th year indicates the period after the conventional life of mine when lower grades are mined in the extended mine life because of the increased gold price.

The life of mine (LoM), payback period and internal rate of return (IRR) of the mine based on the conventional waste management and the three scenarios of the proposed waste management systems have been compared in Fig. 10. As expected, the payback period and the IRR were better for the conventional practice compared to the proposed waste management framework. The IRR decreased from 14.1 to 13.2% while the payback period increased from 5.4 to 8.9 years. The estimated life of mine per the implementation of the proposed waste management framework (Scenario 3) will increase by 82.7%, from 16.2 to 29.6 years compared to the conventional waste management practice.

Table 2: Summary of results for conventional and proposed waste management systems

Description	Ore Tonnage	Conventional Practice	Future Price Increase	Future Tech Increase	Future Price & Tech Increase
ORE 1 (gold grade ≥ 0.5 g/t) (Mt)	76.2	62.1	71.2	71.2	71.2
ORE 2 (0.01 < gold grade < 0.5 g/t) (Mt)	22.5	3.0	14.5	13.6	19.9
Total Material Mined (Mt)		65.1	85.7	84.8	91.1
Mineralized Material Processed (Mt)		58.8	80.2	78.5	91.1
Mineralized Material Processed (%)		59.5	81.3	79.5	92.3
Unmined and Unprocessed Mineralized Material (Mt)		39.9	18.5	20.2	7.6
Stripping Ratio		2.58	5.46	5.52	5.08
NPV (MC$)		379.9	374.4	249.3	427.6
NPV Compared to Conventional (%)		0.0	-1.4	-34.4	12.6
Life of Mine (Years)		16.2	28.4	28.4	29.6
Payback (Years)		5.4	8.9	8.9	8.9
IRR (%)		14.1	12.9	12.4	13.2

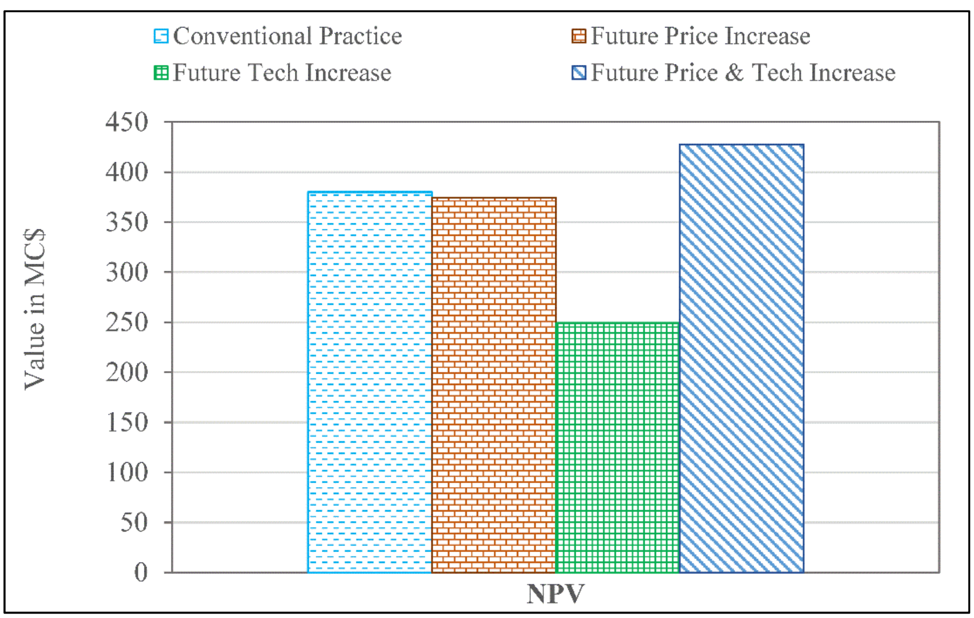

Fig. 8: Comparison of estimated NPV

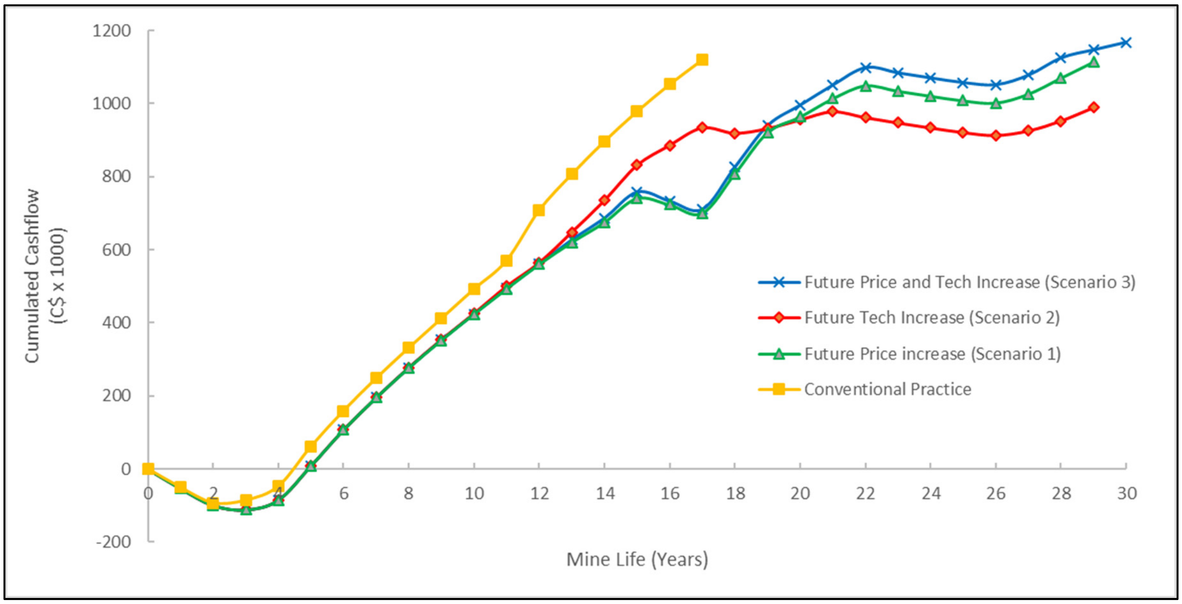

Fig. 9: Comparison of cumulative cashflows

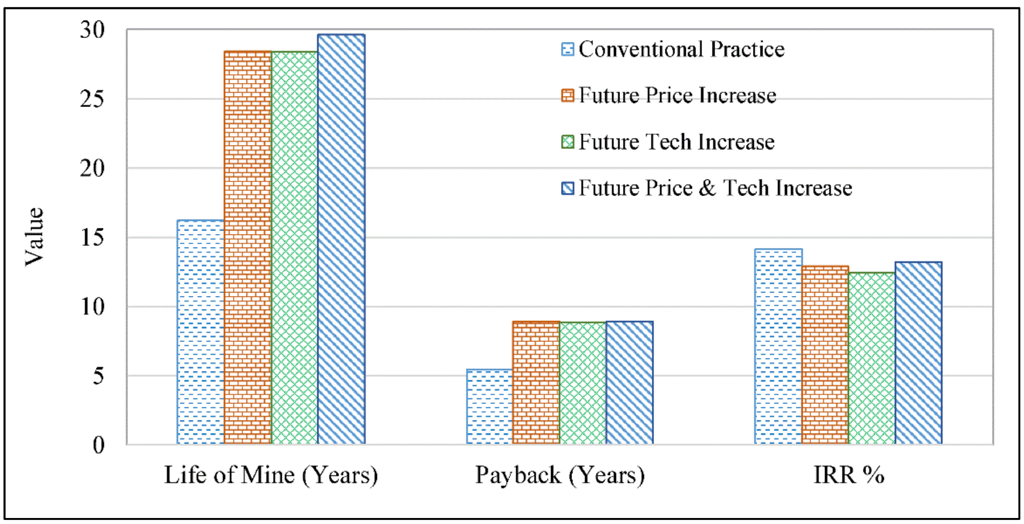

Fig. 10: Comparison of estimated life of mine, payback period and internal rate of return

4. Conclusions

The conventional waste management system does not consider the possibility of mining the mineralized waste during the life of mine. This system abruptly assumes that mining only continues until the ore is economically depleted rather than physical depletion. The potential of the mineralized waste possibly becoming beneficial in the future based on changes in the mineral prices, processing plant recovery or both are not typical considerations of most current strategic mine plans.

The utmost concern is the quantity of mineralized resources that are left unmined in the ground, sent to waste dumps or unprocessed. This reduces the overall mineral resource and the global minerals availability. The conventional waste rock management practice results in mineralized waste materials being extracted from the ground and not evaluated for their potential but rather mixed with non-mineralized waste materials and further left occupying larger surface areas with all its associated environmental challenges. The mineralized waste rock that is completely mixed with the non-mineralized waste rock on the waste dump will lose its asset value since it can no longer be processed.

The proposed waste management framework ensures that, mineral resources are planned towards physical depletion as opposed to the current economic depletion strategy of the mining industry. Evaluation of the proposed framework with the case study indicates 92.3% depletion ratio as opposed to 59.5% depletion ratio per the conventional practice. The additional 13.4 years mine life will enhance sustainability of the mine, employability of workers, positive societal impacts and continual flow of governmental tax benefits. In addition, the proposed framework will further reduce environmental footprints. The future economic benefits of the mine during the implementation of the proposed waste management framework, coupled with several social and economic benefits of the country hosting the mineral deposit is worth exploring.

5. Recommendations

Mining companies should explore the proposed mining and waste management framework presented in this paper during their strategic long-term mine planning. With lessons from Directive 082 (Ellis, 2016), resource rich countries should establish a legislative minimum cut-off grade or an index to determine the minimum cut-off grade of mineral deposits. If the economic cut-off grade is higher than the legislative cut-off grade, then companies must stockpile and document the mineralized resource, and then filed with the government for potential extraction in the future. Furthermore, mining regulations of these countries should be amended to ensure mining companies operate with a legislated minimum processing plant recovery below which they must be investigated.

For extended mine life, governments should consider supporting companies to sustain their mining operations after the economic mine life based on the conventional mining and waste management system. Some of the suggested supports include: 1) tax reliefs or tax reductions; 2) low interest rate government loans; and 3) reduction of fees charged on mining machinery imported.

Future research works are required to evaluate the potential of tailings generated throughout the life of mine as a future mineral resource. Further efforts should also be made to forecast mining cost into the future as new mining systems like autonomous mining and larger more efficient mining equipment have the potential to reduce mining cost as shown by historical trends.

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