Balancing Economic Development & Environmental Protection in Ajax Mine

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Executive Summary

The mining industry is one of the vital pillars of the Canadian economy, also serving as one of the main economic drivers in British Columbia. With the development of the mining industry, associated impacts on the environment and community have attracted more attention in recent years. The object of our research is the proposed Ajax Mine in Kamloops, BC. We use a mathematical tool (i.e., goal programming) to investigate the relation between the mine's probability and environmental impact to the surrounding community.

First, we collected the opinions and concerns expressed in public forums, media articles and community reports, as well as Ajax news releases and public documents. After analyzing the public responses and company's objectives, we concentrated on five issues related to the proposed mine, namely air emissions, waste water, recycled water, productivity and profit, and then constructed a mathematical model to include these five factors as the main constraints.

Second, we formulated Ajax's processes and operations as a goal programming model, with annual tonnes of ore milled as the main input variable. The economic interest, specifically in terms of profit, was set as the first level of priority, and the environmental impacts, including air emissions, waste water and recycled water, are set as the second level of priority. In addition, the lower limit of the copper, gold production and the annual tonnes of ore were set as the functional constraints.

The data collection was a major challenge in this research, because Ajax declined to provide its production parameters or design specifications before the Environmental Assessment Application is released. We used the data which appeared in the public documents as our main sources. In cases where data was unavailable, we relied on research articles or similar mining operations in Canada as sources for our data collection. After making some technical assumptions, optimization software Lingo was used to solve the mathematical model.

There were twelve different scenarios of the mining processes of drilling, blasting and hauling to be considered. The outputs of the original model show that the first scenario generated the largest profit for Ajax, US$247.972 million, but also produced the highest level of dust emissions, at 2176.293 tonnes; the twelfth scenario had the least impact on air quality with dust emissions of 1285.315 tonnes but also generated the lowest profit, US$239.43 million. The analysis confirms the general belief that air emissions decrease while the economic value increases, and vice versa. It is interesting to note that the methods of blasting have the greatest impact in the reduction of dust.

Furthermore, we conducted sensitivity analysis to illustrate the effects of the changes in conditions, such as volatility of commodity prices, adoption of technology, and the like: 1) we changed the order of the two priorities, making the environmental concerns the first level of priority and the economic benefit the second, and except for the first deviations, the optimal results of the air emissions, waste water discharges and profits did not change, which shows the enormous stability of this model; 2) by changing the assumption of the cost of blasting with water cartridges, the results of the analysis show that optimal profit increases when the cost of blasting with water cartridges declines. The result provides good evidence that blasting with water cartridges would be the most effective for cost reduction and dust-control; 3) analysis of copper and gold prices shows that copper prices have greater impact on optimal profits than gold prices; 4) <u>if we set a relatively low standard of air emission (i.e., 75% of HVC's air emission), with better dust-control methods, Ajax can achieve air emission targets and exceed its</u>

economic objective with the current commodity price. However, if the standard of air emissions is raised (e.g., 40% of HVC air emission), Ajax may fail to meet the standard even using the all three best dust-control methods available (resp. exceed by 34.34%). Hence, with the higher environmental standard, the three dust-control methods studied in this project would be insufficient and other new technologies or more effective dust-control methods would be required in order to meet the stricter standard.

Finally, the future investigation of our model is discussed. With more time and additional data, we could refine the model in four ways by including wind factors, water recycling, more variables and multi-year projections.

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1. Introduction

1.1 Background

Mining is one of Canada's most important economic sectors, with more than 800 mines across the country directly employing more than 363,000 workers. As a global leader in mining, Canada has 11 major minerals and metals, ranking in the top five countries in global production. Particularly in British Columbia, mining is a major driver of development and sustained economic activity throughout the province, where it offers employment, education and economic growth opportunities.[1]

Although mining has been key to Canadian settlement and development, in recent decades the industry has also been criticized for its environmental and social impacts. Along with the benefits of mining development, issues regarding air pollutants, discharged water, solid waste and other aspects are sources of concern for mining communities. Finding methods to balance environment protection with the development of mining operations is a strategic move to maintain a sustainable mining industry and to protect a community's well-being.

1.2 This Project

Our research object is KGHM International's Ajax Mine, a proposed open pit copper and gold mine near the city limits of Kamloops of the population 85,000 in British Columbia. The proposal has generated much debates and controversy among the citizens of Kamloops. Those in favour of the mine promote the job prospectives and economic benefits to be brought by the Ajax project, while those against the project question the environmental impacts and related health issues. Several reports on the Ajax project and the impact generated by it have been released. For example, Wardop[16] gives a comprehensive review of all operations at Ajax and provides a detailed account of the *accounting profit* for the mine's life span; Tsigaris[6] investigates the *economic profit* (which includes opportunity cost beyond the accounting profit) of Ajax by providing an assessment of operating costs as well as the possible health costs and mortality caused by deteriorating air quality in the city; Karpiak *et al*.[5] use cost-analysis to estimate the economic benefits from local employment and indirect economic contributions to the region's economy, along with the costs involved, such as social, health and welfare issues, as well as indirect costs including subsidized electricity, clean up and site mediation costs, lost real estate values and lost property tax revenues.

In consideration of these analyses and assessments, we aimed to construct a framework of quantitative analysis (i.e., a mathematical model) to take into account all factors and issues described in the previous studies. The framework enabled us to evaluate the direct impact of Ajax's mining operation upon the local community, and to explore the trade-off between the *accounting profit* of Ajax mine and its environmental impact in terms of air pollution, waste water discharge and recycled waste water. The goal of our project was to maximize company revenue regarding Ajax, while minimizing its environmental and health impacts on the community.

1.3 Methodology Used: Goal Programming

Because we were considering multiple objectives in the investigation, we adopted a method known is Multi-Criteria Decision Analysis (MCDA), which can resolve the issue of conflicts between economic development and environmental protection. In this project, Goal Programming, the commonly used method to solve MCDA, was adopted.

Goal programming is a method to solve linear programming with multiple objectives, with each objective viewed as a "goal". In goal programming, d_i^+ and d_i^- (deviation variables) are used to denote the amounts of overachievement or underachievement of a targeted goal i. The goals themselves are added to the constraint set with d_i^+ and d_i^- acting as the surplus and slack variables. In goal programming, we satisfy goals in a sequence of priorities. Second-priority goals are pursued without reducing the first-priority goals, etc.[2]

1.4 Ajax Mine Review

The Ajax property is 100% owned by KGHM Ajax Mining Inc., a joint venture company owned 80% by KGHM Polska Miedz S.A. (KGHM) and 20% by Abacus Mining & Exploration Corp (Abacus).[3]

The Ajax project, located south of City of Kamloops, British Columbia (BC), will be an open pit copper and gold mine producing 60,000 tonnes per day (t/d) ore for processing. Approximately 87% of the main project infrastructure footprint will be located on private land owned by KAM, with approximately 13% utilization of Crown land[25] (Figure 1.1). The primary components are proposed to be adjacent to Kamloops city limits. The closest facility is approximately 850 metres from the City of Kamloops' Urban Growth Boundary, approximately 1.4 km from the Knutsford community, and approximately 1.7 km from the neighbourhood of Aberdeen. Since nowhere in Canada is there a mine so close to a city with such a large population (about 86,000), the mine will have a major impact on community life.

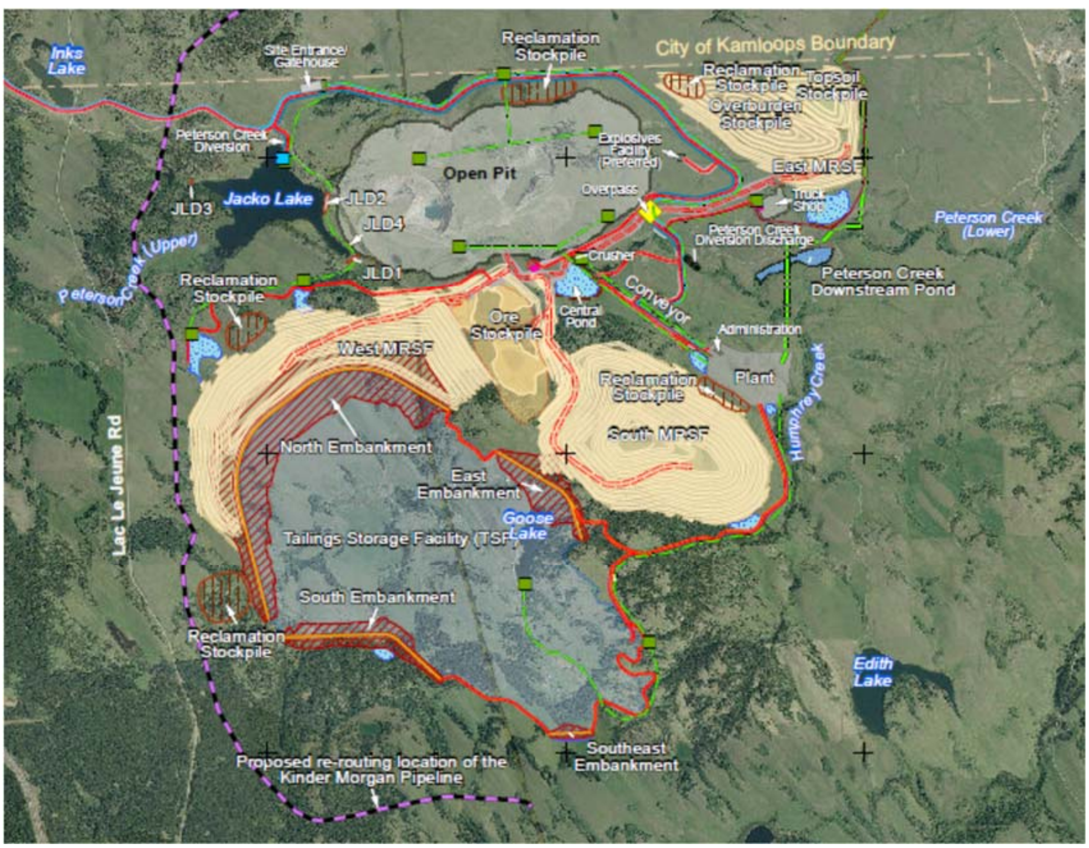

Figure 1.1 Location of Ajax Mine

After starting operations, Ajax will mine and process 60,000 t/d materials and plans to have an annual production of 109 million pounds of copper and 99,000 ounces of gold. During its 23-year mine life, Ajax may provide about 500 full-time technical, mining services, health and safety, and administrative positions.[4] The mine will be beneficial to the local and provincial economies.

1.5 Ajax Mine & Community

Generally, metal mining impacts the surrounding area in several ways, for instance, energy usage, biodiversity, employees, materials reclamation, discharge and recycling of water, community health, and so on.

Figure 1.2 Impact of Metal Mining on a Community

The concerns from the community regarding the Ajax proposal mainly focus on air pollution, noise, vibration, health, and the use, discharge and recycling of water.

1.5.1 Air

There are mainly six types of air pollutants: metal powders, particulate matter, ozone, sulfur dioxide, nitrogen oxides, and carbon monoxide.[5] The flow of these pollutants into the atmosphere, carried by prevailing winds over the City of Kamloops may promote serious health problems. From the report [5], particulate matter (PM) is identified as a primary concern. PM relevant to health refers to mass concentrations of particles with a diameter of less than 10 µm (PM10) and of particles with a diameter of less than 2.5 µm (PM2.5). PM10 and PM2.5 include inhalable particles that are small enough to penetrate the thoracic region of the respiratory system. The exposure to PM10 and PM2.5 can result serious damage to human health over both the short term (hours, days) and long term (months, years), including respiratory and cardiovascular morbidity, such as aggravation of asthma, respiratory symptoms and an increase in hospital admissions, and mortality from cardiovascular and respiratory diseases and from lung cancer. There is good evidence of the effects of short-term exposure to PM10 on respiratory health, but for mortality, and especially as a consequence of long-term exposure, PM2.5 poses a stronger risk factor than the coarser PM10 (particles in the 2.5–10 µm range). All-cause daily mortality is estimated to increase by 0.2–0.6% per 10 µg/m3 of PM10.[21] Long-term exposure to PM2.5 is associated with an increase in the long-term risk of cardiopulmonary mortality by 6–13% per 10 $\mu g/m^3$ of PM2.5.[22, 23] Based on the above facts, we paid special attention to levels of additional PM10 and PM2.5 generated by the Ajax project.

The largest size particle that can be suspended in air for long periods of time from wind velocity acting upon it is about 60 µm, which is about the thickness of a human hair.[20] Thus, in relation to dust impacts, we also considered total suspended particulate (TSP).

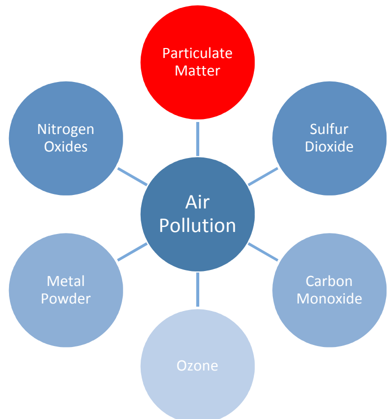

Figure 1.3 Air Pollutants from Copper-Gold Mines

1.5.2 Noise

Regarding noise, Ajax promises to adopt the following practices in order to reduce noise to the nearby communities:[16]

- Create sound reduction berms to prevent the dispersal of transient noise from the mine processing area;
- Perform blasts only during dayshift to minimize the impact of blasting noise on neighboring residents.

It seems that the noise issue could be managed and the concerns from the community could possibly be addressed to a satisfactory level if the promised procedures above are implemented.

1.5.3 Vibration

Ajax states the following in regard to vibration impacts:[7]

- "The ground vibration will measure two mm/s, which is 10 times less than the threshold for damage to drywall. Air blasts will not exceed 120 dBL at Aberdeen and will not be noticed by at least 95 per cent of the local population";
- "Studies have shown that as long as blasting is done at safe levels, the cumulative effects of blasting on structures is practically non-existent. At the levels predicted from the Ajax Mine, it would take 600 to 800 years of blasting to cause fatigue damage in drywall in a home";
- "Our model indicates a peak particle velocity of 3 millimeters/second in the Aberdeen Area (2 kilometers from the edge of pit) with a charge weight of 2,372 kilograms per delay. The Ontario caution limit in 10mm/s. The human perception level of 1 millimeter/second is modeled at a distance of 4 kilometers from the edge of the pit with a charge weight of 2,372 kilograms delay."

From Ajax's statements, it seems that the issue of vibration will not be a major concern compared to others. Based on this judgement, we decided to ignore vibration in our study. However, it can be included and analyzed in our model without much difficulty in case other professional opinions show it to be a major disturbing factor.

1.5.4 Water

Water discharge and intake are two major concerns of the community. Ajax has not responded to the problem of discharged water or seemingly provided a feasible solution to it. In regard to the intake issue, Ajax claims that the mine will require 2000 m^3/hr, which equates to 0.56 m^3/s from Kamloops Lake and that wetted width would be reduced by 9cm to 29cm and maximum depth reduced by 2 mm to 5 mm at these cross sections as a result of proposed water withdrawal.

Based on the discussion above, we focus our attention mainly on air emissions, water discharge and water recycling.

1.6 Mining Process in Ajax

To establish the balance model, the mining process in Ajax, especially those processes which will have major impact on environment, must be studied thoroughly. Since the Ajax mine operations are still under review, and plans indicate that operations will start in 2020, a flow chart of its operating process was made according to its plan and feasibility study.[16] The flow chart shows the essential mining processes in Ajax Mine, including blast-hole drilling, open-pit-mine blasting, loading, hauling, crushing, grinding, flotation and concentration, etc.

The mining process of Ajax is similar to other copper-gold mines. Among the mining processes, attention will mainly focus on those which will generate pollutants and have the most impact on living conditions in the community.

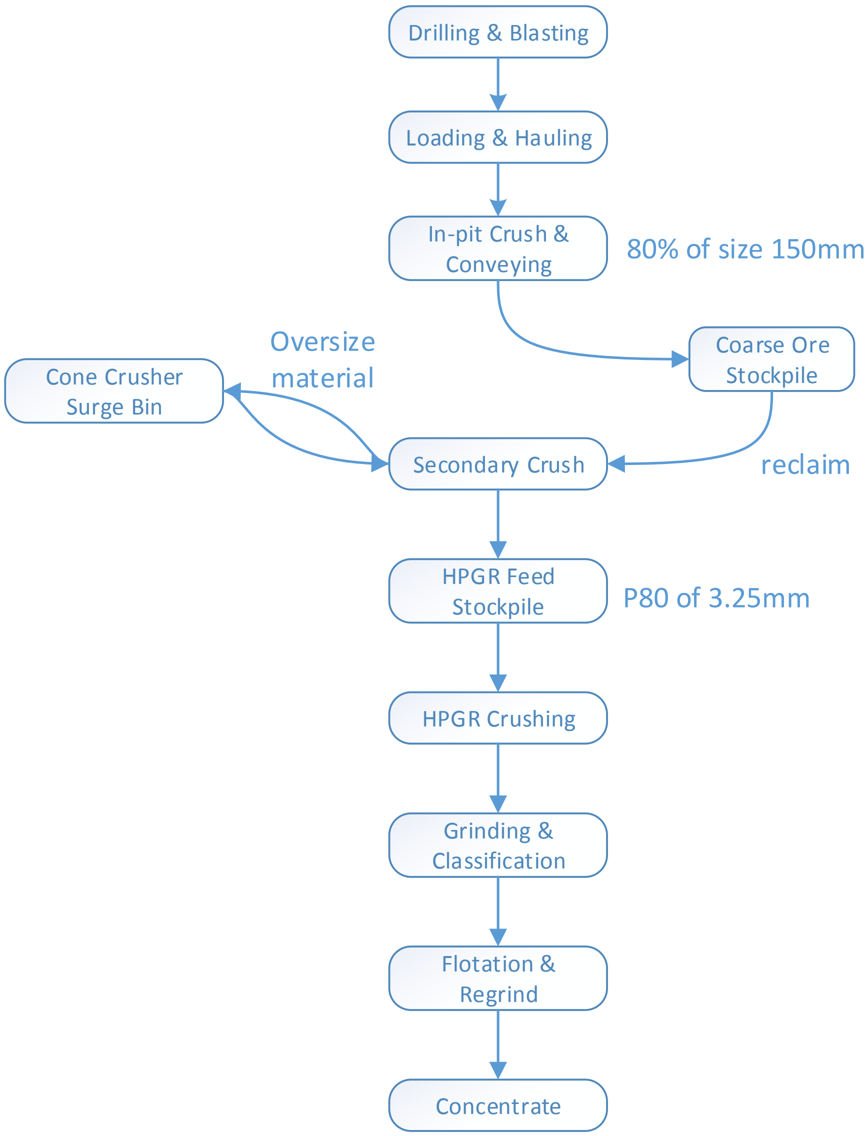

Figure 1.4 Ajax Proposed Mining Processes

2. Building the Ajax Mine Balance Model

2.1 Structure of the Model

According to the analysis in 1.5.3, our goals can be separated into two parts—economic and environmental, and each part can be subdivided into several parts, as shown in Figure 2.1.

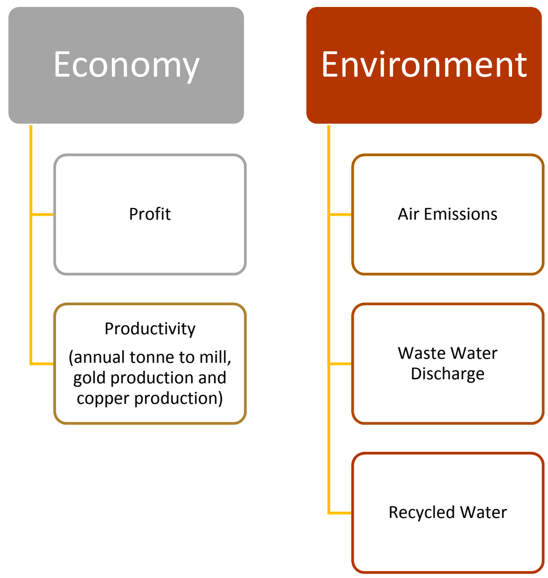

Figure 2.1 Structure of Balance Model

Under Economy, profit and production are considered. Production contains three parameters: the annual tonne to mill, gold production, and copper production. Environmental aspects include four factors: air emissions, waste water discharge, recycled water, and noise and vibration.

There are several methods available to complete the same task for each process, and different methods can result in different impacts on environment and also generate different costs. To keep our model simple and robust, we decided to use only one variable, the total annual tonnes to mill, with all economic and environmental targets to become functional or goal constraints. Under one scenario with a certain method selected in every process, the optimal total amount of tonnes to mill is obtained through goal programming. We analyzed the results under all the possible scenarios to see which scenario would be the most beneficial for Ajax and community.

2.2 Functional and Goals Constraints

First, we needed to identify the available technologies or methods for each major process in open-pit mining, and its economic values and environmental impacts. With this information, functional and goal constraints could be established.

2.2.1 Air Emission

There are four processing sections which will generate particulate matter: drilling, blasting, loading and hauling (Figure 2.2). Drilling, blasting and hauling employ different methods to control dust.

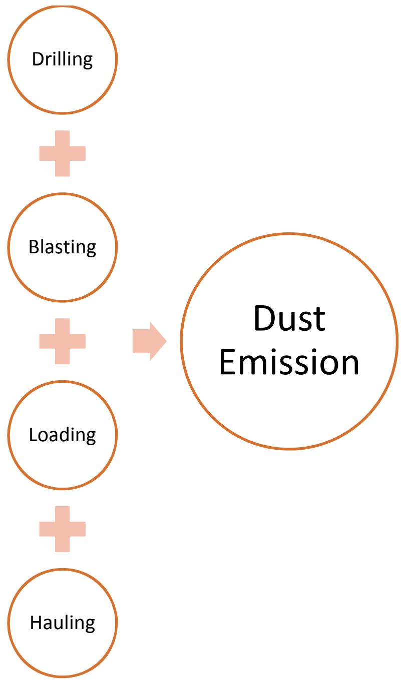

Figure 2.2 Processes Which Generate Dust

Drilling

Drilling operations are notorious sources of respirable dust, which can lead to high exposure levels for the drill operator, drill helper, and other personnel in the local vicinity during operation. Therefore, dust controls on drills are necessary and involve both wet and dry methods.[8]

Figure 2.3 Drilling in Franke Mine

(Another copper mine belonging to KGHM in Chile, Source: http://www.ajaxmine.ca/gallery)

In Ajax's *Feasibility Report*, other measures used for the drilling process are mentioned: [16]

"A wall control program consisting of pre-splitting and cushion blasts will be carried out along all ultimate walls including the intermediate pit phases. This wall control pattern will include a three-row trim blast and a pre-shear line. Two lines of the trim or cushion pattern will be drilled with the production drill rig. The last cushion blast line and the pre-shear holes will be drilled with a percussion drill."

--Section 16.4.2

Feasibility Study Technical Report, Ajax Copper/Gold Mine

Note: Wall control program is mainly for the control of ground shake wave, noise and structure of benches. While in the meantime it can also reduce the air pollutants in a way.

In the dust control handbook, there are two types of drilling methods related to air emissions:

*"There are two basic methods for controlling dust on drills: either **a wet suppression system** or **a dry cyclone/filter type collector**."*

"Wet systems operate by spraying water into the bailing air as it enters the drill stem."

"Dry collectors operate by withdrawing air from a shroud or enclosure surrounding the area where the drill stem enters the ground."

--Chapter 3: Drilling and Blasting

Dust control handbook for industrial mineral mining and processing

According to the information above, drilling is divided into two parts: wet drilling and dry drilling with a dust collector. It is known that wet drilling is the best method for dust control in surface drilling, while wet drilling requires a larger amount of water and shortens machine life by 50% or more.[8]

Blasting

In Ajax's *Feasibility Report*, dust control for blasting is mentioned briefly:[16]

*"**Dust control** and vibration reduction for blasting has been taken into consideration."*

--Section 16.4.3 Blasting

Feasibility Study Technical Report, Ajax Copper/Gold Mine

The dust control handbook outlines five dust-control methods that can be used for underground mining:

"*There are five methods of dust suppression that can be used for the control of dust during blasting, <u>many of which are effective for underground mining only</u> [Cummins and Given 1973]:*

- *wetting down the entire blasting area prior to initiating the blast;*
- *the use of water cartridges alongside explosives;*
- *the use of an air-water fogger spray prior to, during, and after initiating the blast;*
- *the use of a filtration system to remove pollutants from the air after the blast; and*
- *dispersal and removal of the dust and gases using a well-designed ventilation system."*

--Chapter 3: Drilling and Blasting

Dust control handbook for industrial mineral mining and processing

Among the five methods shown above, the second method using water cartridge can be implemented in an open-pit mine (Figure 2.4). Measures for blasting can be analyzed for water cartridge use and without water cartridges.

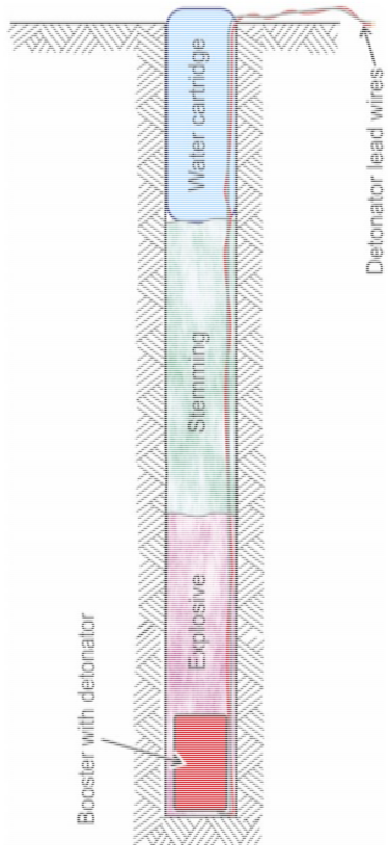

Figure 2.4 Blasting with Water Cartridges[8]

Loading and Hauling

As the *Feasibility Study Report* mentioned, some watering measures will be taken to control road dust:

*"**Routine water spraying** by two water trucks will suppress **dust generated on roads, benches, and dump areas.** Non-chloride dust suppressants may be applied in high traffic areas if necessary. During winter, graders will be used to blade snow over road surfaces as required to minimize dust."*

--Section 16.14 Emission Control

Feasibility Study Technical Report, Ajax Copper/Gold Mine

Water spraying methods used for hauling can be classified into several grades according to their dust-control effects and costs.

Air Emission Goal Constraint

Air emissions can be expressed as one goal constraint, to achieve the air emission target.

$$\underbrace{(\beta_{11}\alpha_{11}+\beta_{12}\alpha_{12})M}_{drilling}+\underbrace{(\beta_{21}\alpha_{21}+\beta_{22}\alpha_{22})M}_{blasting}+\underbrace{\alpha_3 M}_{loading}+\underbrace{(\beta_{41}\alpha_{41}+\beta_{42}\alpha_{42}+\beta_{43}\alpha_{43})M}_{hauling}=T_{air}+d_{air}^{+}-d_{air}^{-}$$

Where, β_{ij} is the 0-1 variable:

$$\begin{cases}\beta_{11}=0\, and\ \beta_{12}=1,\ chose\ wet\ drilling\\ \beta_{11}=1\, and\ \beta_{12}=0,\ chose\ dry\ drilling\ with\ dust\ control\end{cases}$$

$$\begin{cases}\beta_{21}=0\, and\ \beta_{22}=1,\ chose\ balsting\ with\ water\ cartridges\\ \beta_{21}=1\, and\ \beta_{22}=0,\ chose\ blasting\ without\ control\end{cases}$$

$$\begin{cases}\beta_{41}=1\ ,\beta_{42}=0\ and\ \beta_{43}=0,\ chose\ poor\ hauling\ method\\ \beta_{41}=0\ ,\beta_{42}=1\ and\ \beta_{43}=0,\ chose\ fair\ hauling\ method\\ \beta_{41}=0\ ,\beta_{42}=0\ and\ \beta_{43}=1,\ chose\ good\ hauling\ method\end{cases}$$

α_{11} is the amount of dust generated by dry drilling with dust controls when one tonne of ore is milled;

α_{12} is the amount of dust generated by wet drilling when one tonne of ore is milled;

α_{21} is the amount of dust generated by blasting without any dust control when one tonne of ore is milled;

α_{22} is the amount of dust generated by blasting with water cartridges when one tonne of ore is milled;

α_3 is the amount of dust generated by loading when one tonne of ore is milled;

α_{41} is the amount of dust generated by hauling with ‘poor’ measures when one tonne of ore is milled;

α_{42} is the amount of dust generated by blasting with ‘fair’ measures when one tonne of ore is milled;

α_{43} is the amount of dust generated by blasting with ‘good’ measures when one tonne of ore is milled;

T_{air} is the target dust emission, which is considered the tolerable level;

d_{air}^{+} is the surplus of dust emissions;

d_{air}^{-} is the slack of dust emissions.

2.2.2 Waste Water

Flotation is a process to separate minerals from gangue (commercially worthless material) by taking advantage of differences in their hydrophobicity, and is the main source of waste water and water discharged into tailings ponds. The amount of waste water is related to the amount of ore processed.

The goal equation of waste water can be presented as the following:

$$\underset{flotation}{\alpha_5 M} = T_{waste\,water} + d^{+}_{waste\,water} - d^{-}_{waste\,water}$$

where α_5 is the amount of waste water generated in flotation when one tonne of ore is milled,

$T_{waste\,water}$ is the upper limit (target value) of waste water, $d^{+}_{waste\,water}$ is the surplus of waste water and $d^{-}_{waste\,water}$ is the slack of waste water.

2.2.3 Recycled Water

Water is proposed to be recycled from the tailings system.

A water management plan will be required to demonstrate appropriate control of all surface water within the mine area. Goals of the plan include preservation of water quantity and quality downstream of the Project, optimization of water use, maximization of water re-use, minimizing mixing of clean and mine-contact water, managing seepage, utilizing water diversion, and eliminating uncontrolled releases.

The goal equation of recycled water can be presented as the following:

$$\underset{tailings}{(\beta_{61}\alpha_{61} + \beta_{62}\alpha_{62} + \beta_{63}\alpha_{63})M} = T_{recycle\,water} + d^{+}_{recycle\,water} - d^{-}_{recycle\,water}$$

Where,

$$\begin{cases} \beta_{61} = 1 \,,\, \beta_{62} = 0 \text{ and } \beta_{63} = 0, \text{chose poor tailing method} \\ \beta_{61} = 0 \,,\, \beta_{62} = 1 \text{ and } \beta_{63} = 0, \text{chose fair tailing method} \\ \beta_{61} = 0 \,,\, \beta_{62} = 0 \text{ and } \beta_{63} = 1, \text{chose good tailing method} \end{cases},$$

α_{61} is the amount of water recycled in tailings with the poor' tailings method when one tonne of ore is milled;

α_{62} is the amount of water recycled in tailings with the 'fair' tailings method when one tonne of ore is milled;

α_{63} is the amount of water recycled in tailings with the 'good' tailings method when one tonne of ore is milled;

$T_{recyclewater}$ is the lower limit (target value) of recycled water;

$d^{+}_{recycle\,water}$ is the surplus of recycled water;

$d^{-}_{recycle\,water}$ is the slack of recycled water.

2.2.4 Production

Ajax sets goals for the annual production of gold and copper, and also the annual tonnes to mill. Three functional constraints can be established:

Copper production: $\alpha_7 M \geq P_{copper}$

Gold production: $\alpha_8 M \geq P_{gold}$

Annual tonnes to mill: $M \geq P_{planned\ Mill\ Amount}$

where α_7 is the amount of copper produced when one tonne of ore is milled, P_{copper} is the lower limit of copper production; α_8 is the amount of produced gold when one tonne of ore is milled, P_{gold} is the lower limit of gold productivity; M is the total tonnes *milled* per year, $P_{planned\ Mill\ Amount}$ is the lower limit of the milled amount.

2.2.5 Profit

A mine operation's profit is the result of the sales revenue minus expenditures.

- **Sales Revenue**

The main products of the Ajax Mine will be copper and gold, so the sales revenues are from sales of two commodities. Revenue equals the unit price multiplied by the production. Ajax's sales revenue can be expressed as following:

$$sales\ revenue = copper\ price \times copper\ productivity + gold\ price \times gold\ productivity$$

where the production level is the same as that described in Section 2.2.4, and the copper price and gold price are market prices, which are variable with time.

$$R = p_{copper}\alpha_7 M + p_{gold}\alpha_8 M$$

where p_{copper} is the unit copper price and the p_{gold} is the unit gold price.

- **Expenditure**

Expenditures can be split into two parts: fixed costs and variable costs.

- Fixed Costs

Fixed costs consist of taxes and initial capital costs.

Taxes include federal and provincial taxes, mining tax and municipal tax.

$$T_{tax} = T_{\min ing} + T_{municipal} + T_{federal\ and\ provincial}$$

where $T_{\min ing}$ is the mining tax, $T_{municipal}$ is the municipal tax and $T_{federal\ and\ provincial}$ is federal and provincial taxes. The initial capital cost for the Ajax Project is estimated to be approximately US$795 million. With 23-year LOM, the average cost $T_{initial}$ per annum is US$34.565 million.

- Variable Costs

Variable costs include hydroelectricity and costs associated with the different processing methods.

$$T_{\text{var}iable\ cost} = (\beta_{11}\gamma_{11} + \beta_{12}\gamma_{12})M + (\beta_{21}\gamma_{21} + \beta_{22}\gamma_{22})M + (\beta_{41}\gamma_{41} + \beta_{42}\gamma_{42} + \beta_{43}\gamma_{43})M + \gamma_{hydro}M$$

where β_{ij} is the 0-1 variable with the same definition as in Section 2.2.1, γ_{hydro} is the hydro-electricity cost for each tonne milled, α_{ij} is the unit cost for the j th method in the i th mining process for each tonne milled:

γ_{11} is the unit cost for each tonne milled when dry drilling with dust control is implemented;

γ_{12} is the unit cost for each tonne milled when wet drilling is implemented;

γ_{21} is the unit cost for each tonne milled when no blasting measure is implemented;

γ_{22} is the unit cost for each tonne milled when blasting with water cartridges is implemented;

γ_{41} is the unit cost for each tonne milled when the 'poor' hauling method is used;

γ_{42} is the unit cost for each tonne milled when the 'fair' hauling method is used;

γ_{43} is the unit cost for each tonne milled when the 'good' hauling method is used.

- Variable Costs for Smelting

The final products of Ajax mine would be copper concentrate of 25% Cu containing approximately 18 g/t Au. The copper concentrate will be delivered to a smelter to process in order to obtain marketable metals. The various costs involved in this portion of operations include treatment, smelting, refining, possible penalty for moisture, transportation, insurance [16] We use $\gamma_{smelter}$ for the unit cost of smelter-related expenses for each tonne milled.

Profit Summary

The composition of profit can be expressed as the following figure and equations.

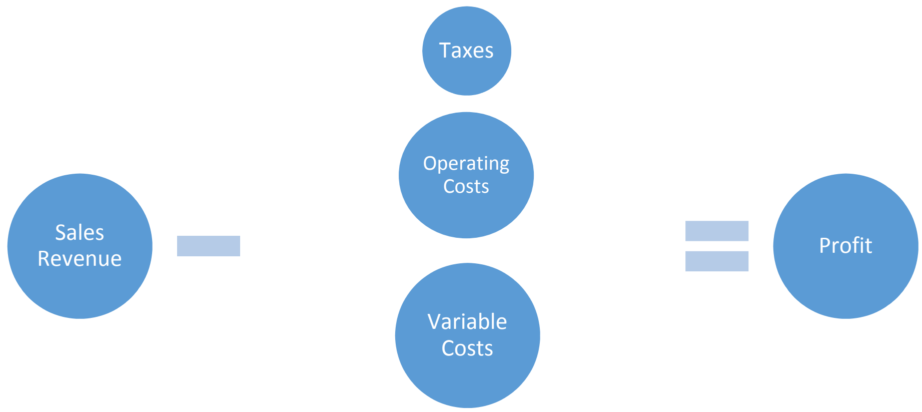

Figure 2.5 Composition of Profit

$$
\begin{aligned}
& p_{copper}\alpha_7 M + p_{gold}\alpha_8 M - T_{initial} - [T_{tax}M + \gamma_{operating\ cost}M + \gamma_{smelter}M \\
& +(\beta_{11}\gamma_{11} + \beta_{12}\gamma_{12})M + (\beta_{21}\gamma_{21} + \beta_{22}\gamma_{22})M + (\beta_{41}\gamma_{41} + \beta_{42}\gamma_{42} + \beta_{43}\gamma_{43})M + \gamma_{hydro}M\,] \\
& = T_{profit} + d^{+}_{profit} - d^{-}_{profit}
\end{aligned}
$$

where T_{profit} is the lower limit of profit, d^{+}_{profit} is the surplus of profit, d^{-}_{profit} is the slack of profit.

2.2.6 Summary of the Functional and Goal Constraints

According to the analysis above, the **goal constraints** can be summarized as the following:

- Air Emissions:

$$\underbrace{(\beta_{11}\alpha_{11} + \beta_{12}\alpha_{12})M}_{drilling} + \underbrace{(\beta_{21}\alpha_{21} + \beta_{22}\alpha_{22})M}_{blasting} + \underbrace{\alpha_3 M}_{loading} + \underbrace{(\beta_{41}\alpha_{41} + \beta_{42}\alpha_{42} + \beta_{43}\alpha_{43})M}_{hauling} = T_{air} + d^{+}_{air} - d^{-}_{air}$$

- Waste Water:

$$\underbrace{\alpha_5 M}_{flotation} = T_{waste\,water} + d^{+}_{waste\,water} - d^{-}_{waste\,water}$$

- Recycled Water:

$$\underbrace{(\beta_{61}\alpha_{61} + \beta_{62}\alpha_{62} + \beta_{63}\alpha_{63})M}_{tailings} = T_{recycle\,water} + d^{+}_{recycle\,water} - d^{-}_{recycle\,water}$$

- Profit:

$$
\begin{aligned}
& p_{copper}\alpha_7 M + p_{gold}\alpha_8 M - T_{initial} - [T_{tax} M + \gamma_{operating\ \cos t} M + \gamma_{smelter} M \\
& +(\beta_{11}\gamma_{11} + \beta_{12}\gamma_{12})M + (\beta_{21}\gamma_{21} + \beta_{22}\gamma_{22})M + (\beta_{41}\gamma_{41} + \beta_{42}\gamma_{42} + \beta_{43}\gamma_{43})M + \gamma_{hydro} M\,] \\
& = T_{profit} + d^{+}_{profit} - d^{-}_{profit}
\end{aligned}
$$

The three **functional constraints** are:

- Copper production:

$$\alpha_7 M \geq P_{copper}$$
$$copper\ production$$

- Gold production:

$$\alpha_8 M \ \geq P_{gold}$$
$$gold\ \ production$$

- Annual tonnes to mill:

$$M \geq P_{planned\ \ Mill\ \ Amount}$$

2.3 Mathematical Model

Based on the processing methods and the principles of goal programming, a mathematical model can be built.

2.3.1 Symbol Description

Table 2.1 Symbol Description

Symbols	Definitions
β_{ij}	0-1 variable
α_{ij}	Waste or Metal generated per tonne of ore milled
M	Annual tonnes to mill
d_i^{+}	Positive deviation variables
d_i^{-}	Negative deviation variables

2.3.2 Priority Level

We have two targets: maximize the company's income and minimize the environmental impact, so we need to place the goals into different priority levels. In this approach, lower priority level goals cannot be attained at the expense of higher priority goals. In this investigation, we set economic goals as having a higher priority than the environmental goals, which means we first satisfy the economic requirement and then minimize impacts on the environment.

The goal equations for the priority levels are:

Priority 1: Maximize economic development.

(Goal 1) Profit is at least P_{profit}**:**

$$p_{copper}\alpha_7 M + p_{gold}\alpha_8 M - T_{initial} - [T_{tax}M + \gamma_{operating\ cost}M + \gamma_{smelter}M$$
$$+(\beta_{11}\gamma_{11} + \beta_{12}\gamma_{12})M + (\beta_{21}\gamma_{21} + \beta_{22}\gamma_{22})M + (\beta_{41}\gamma_{41} + \beta_{42}\gamma_{42} + \beta_{43}\gamma_{43})M + \gamma_{hydro}M\,]$$
$$= T_{profit} + d^{+}_{profit} - d^{-}_{profit}$$

MINIMIZE d^{-}_{profit}

Priority 2: Minimize impacts to the environment.

(Goal 2) Air pollutants are no more than T_{air} **:**

$$\underbrace{(\beta_{11}\alpha_{11} + \beta_{12}\alpha_{12})M}_{drilling} + \underbrace{(\beta_{21}\alpha_{21} + \beta_{22}\alpha_{22})M}_{blasting} + \underbrace{\alpha_3 M}_{loading} + \underbrace{(\beta_{41}\alpha_{41} + \beta_{42}\alpha_{42} + \beta_{43}\alpha_{43})M}_{hauling} = T_{air} + d^{+}_{air} - d^{-}_{air}$$

MINIMIZE d^{+}_{air}

(Goal 3) Waste water is no more than $T_{waste\,water}$ **:**

$$\underbrace{\alpha_5 M}_{flotation} = T_{waste\,water} + d^{+}_{waste\,water} - d^{-}_{waste\,water}$$

MINIMIZE $d^{+}_{waste\,water}$

(Goal 4) Recycled water is at least $T_{recycle\,water}$ **:**

$$\underbrace{(\beta_{61}\alpha_{61} + \beta_{62}\alpha_{62} + \beta_{63}\alpha_{63})M}_{tailings} = T_{recycle\,water} + d^{+}_{recycle\,water} - d^{-}_{recycle\,water}$$

MINIMIZE $d^{-}_{recycle\,water}$

The four weights for the four goals are k_1, k_2, k_3 and k_4, respectively. The general goal is the following:

$$\min \quad P_1(k_1 d^{-}_{profit}) + P_2(k_2 d^{+}_{Air} + k_3 d^{+}_{waste\,water} + k_4 d^{-}_{recycle\ water})$$

The four weights are set to be 1, so the general goal looks like:

$$\min \quad P_1 d^-_{profit} + P_2 (d^+_{Air} + d^+_{waste\,water} + d^-_{recycle\ water})$$

2.4 Formulation Summary

$$\min \quad P_1 (k_1 d^-_{profit}) + P_2 (k_2 d^+_{Air} + k_3 d^+_{waste\,water} + k_4 d^-_{recycle\ water})$$

$$s.t.$$

$$\begin{cases} p_{copper}\alpha_7 M + p_{gold}\alpha_8 M - T_{initial} - [T_{tax}M + \gamma_{operating\ cost}M + \gamma_{smelter}M \\ +(\beta_{11}\gamma_{11} + \beta_{12}\gamma_{12})M + (\beta_{21}\gamma_{21} + \beta_{22}\gamma_{22})M + (\beta_{41}\gamma_{41} + \beta_{42}\gamma_{42} + \beta_{43}\gamma_{43})M + \gamma_{hydro}M] = T_{profit} + d^+_{profit} - d^-_{profit} \\ (\beta_{11}\alpha_{11} + \beta_{12}\alpha_{12})M + (\beta_{21}\alpha_{21} + \beta_{22}\alpha_{22})M + \alpha_3 M + (\beta_{41}\alpha_{41} + \beta_{42}\alpha_{42} + \beta_{43}\alpha_{43})M = T_{air} + d^+_{air} - d^-_{air} \\ \alpha_5 M = T_{waste\,water} + d^+_{waste\,water} - d^-_{waste\,water} \\ (\beta_{61}\alpha_{61} + \beta_{62}\alpha_{62} + \beta_{63}\alpha_{63})M = T_{recycle\,water} + d^+_{recycle\,water} - d^-_{recycle\,water} \\ \\ \alpha_7 M \geq P_{copper} \\ \alpha_8 M \geq P_{gold} \\ M \geq P_{planned\ Mill\ Amount} \end{cases}$$

3. Data Collection

3.1 Air Emissions

3.1.1 Drilling

There are two kinds of drilling methods: wet drilling and dry drilling with dust collection. In fact, there is also a dry drilling method without dust collection, however, it is rarely used at present. Generally, the respirable dust produced in dry drilling without collection is 16 mg/m^3.[8]

Testing has shown that the wet drilling method can provide dust control efficiencies up to 96 percent. Wet drilling has been found to be the best method of dust control, with dust reductions ranging from 86 to 97 percent depending upon the type of drilling involved.[8]

Dry drilling with dust collection produces dust reduction of up to 25 percent compared with dry drilling alone. These systems have the ability to operate in various climates, i.e., they are not subject to the freezing at lower temperatures as with the use of water, and can be up to 99 percent efficient if properly maintained.[8]

In one investigation, drilling operations produced 3.62 g/ton dust (NTIS, 1976).[9]

According to the above, we can calculate the drilling coefficients as following:

$$\alpha_{11} = [1 - 25\% \times 99\%] \times 3.62 = 2.7241 g / t$$

$$\alpha_{12} = \begin{cases} [1-96\% \times 86\%\ ] \times 3.62 = 0.6313 g/t, \text{ when reduction is } 86\% \\ [1-96\% \times 97\%] \times 3.62 = 0.2491 g/t\ , \text{ when reduction is } 97\% \end{cases}$$

Taking the average of the reduction, we have $\alpha_{12} = [1-96\% \times 91.5\%] \times 3.62 = 0.4402 g/t$.

3.1.2 Blasting

The blasting method can be divided into two groups: using water cartridges and not using water cartridges.

In coal mining operations, the use of these cartridges is claimed to reduce dust by 40–60 percent.[8]

In one study, blasting operations were measured to produce 72.5 g/ton of dust (NTIS, 1976). [9] So we can calculate the blasting coefficients as following:

$$\alpha_{21} = 72.5 g/t$$

$$\alpha_{22} = \begin{cases} [1-40\%] \times 72.5 = 43.5 g/t, \text{ when reduction is } 40\% \\ [1-60\%] \times 72.5 = 29 g/t\ , \text{ when reduction is } 60\% \end{cases}$$

Taking the average of the reduction, we have $\alpha_{22} = [1-50\%] \times 72.5 = 36.25 g/t$.

3.1.3 Loading

Based on the literature, air emissions in truck loading by power shovel (batch drop) are 18g/t and air emissions in end dump truck unloading (batch drop) are 4g/t. Air emissions in loading are 22g/t in total.

$$\alpha_3 = 22 g/t$$

3.1.4 Hauling

There are three different levels of dust control in relation to hauling methods:

Table 3.1 Hauling Methods and Reduction of Emission

Level for Hauling methods	Reduction of emission
Level 1 Watering (2 litres/m^2/h)	50%
Level 2 Watering (>2 litres/m^2/h)	75%
Sealed or salt-encrusted roads	100%

According to the National Energy Research, Development and Demonstration Council (NERDDC) of Australia, the total suspended particulate emission factor for dumping overburden is 12 g/t.

Therefore hauling coefficients are:

$$\alpha_{41} = 50\% \times 12 = 6g / t$$
$$\alpha_{42} = 25\% \times 12 = 3g / t$$
$$\alpha_{43} = 0\% \times 12 = 0$$

3.1.5 Upper Limit of Air Emission

Based on the information from public reports, [12] in 2012 Highland Valley Copper (HVC) released 6,251 tonnes of PM10 and 2,335.3 tonnes of PM2.5. To tackle air emission problems, HVC has taken many steps to reduce the output of dustfall. For example, to eliminate a major source of fugitive dust in mine operations, in 2006 HVC started a 5 ½ year, $25-million project to tackle the problem of dust from ore piles, which involved covering the crushed ore stockpile with three 100 m diameter by 35 m high dome structures to cover each of its three stockpiles. The new covering completely eliminated fugitive dust from ore piles. In comparison, Ajax has indicated in its modified proposal [25] to cover the ore piles but did not state clearly the kind of device to be used. We suspect Ajax may not reach the same level of success (i.e., 0% fugitive dust) as HVC did and thus will produce more total PM from this part of its operations. In other operations, HVC already has many dust control measurements in place (e.g., watering hauling routes). We expect Ajax to take similar measures to reduce air emissions.

To set the upper limit of air emissions, we concentrated on the main component of dust, PM10, which are particles less than or equal to 10 micrometers in diameter and are so small that they can infiltrate the lungs, potentially causing serious health problems. One may want to set an upper limit on PM2.5 instead of that of PM10, since PM2.5 is considered even more dangerous than PM2.5. In this case, our model can be easily modified to accommodate the corresponding analysis.

We use HVC's PM10 emission level (6,251 tonnes) as a benchmark. Because HVC is relatively farther away from any large community but the Ajax mine site is only a few kilometers away from residential areas, we set 40% of HVC's PM10 emissions as a starting point. HVC has more production than the proposed Ajax mine, so the rate of productions of the two companies is also considered.

$$T_{air} = \frac{\text{HVC Air Emission}}{\text{HVC Total Rock Removed}} \times 40\% \times \text{Ajax Total Rock Removed}$$

The HVC total rock removed is 89,000,000 tonnes and the Ajax total rock removed is 74,500,000 tonnes. The upper limit of the air emission is set to be.

$$T_{air} = \frac{6,251,000,000}{89,000,000} \times 40\% \times 74,500,000 = 2,093,000,000 \ (unit: gram)$$

3.1.6 Summary of the Air Emissions Equations

The air emissions equation is as follows:

$$\begin{aligned}&(2.7241\beta_{21} + 0.4402\beta_{22})M + (72.5\beta_{31} + 36.25\beta_{32})M + 22M + (6\beta_{41} + 3\beta_{42})M \\ &= 2,093,000,000 + d_{air}^{+} - d_{air}^{-} \quad (unit: g)\end{aligned}$$

3.2 Waste Water

Metal mines that chemically process ore to concentrate metals such as copper and gold use much more water than non-metal mines such as coal, salt, or gravel mines.

In 2013, Malartic Mine discharged 3,382,221 m^3 waste waterin the course of milling 17,024,120 tonnes of ore. [13] As a result, we can calculate α_5 as:

$$\alpha_5 = \frac{3,382,221}{17,024,120} = 0.1986 m^3 / t$$

Based on the same standard from Malartic, the estimated discharge water for Ajax should be (assume same ratio of ore and waste at Ajax and Malartic):

$$74,500,000 * \frac{17,024,120}{58,434,000} * 0.1986 = 4,310,568 m^3$$

According to the above, we have the recycled water equation:

$$0.1986M = 4,310,568 + d^+_{wastewater} - d^-_{wastewater} \quad (Unit : m^3)$$

3.3 Recycled Water

We lacked recycled water data, so this part is not included in our model.

3.4 Production

The average grades in Ajax Mine are 0.267% Cu and 0.170 g/t Au.

There are several different estimations for proposed copper and gold productivities at the Ajax site:

- In the KGHM Ajax Project official website, the project details include annual production of *109 million pounds of copper and 99,000 ounces of gold.*[14]
- In Abacus Mining & Exploration Corp official website average annual production was estimated at *106 million pounds of copper and 99,400 ounces of gold* in concentrate.[15]
- A table in 22.2 *Pre-tax Model in Feasibility Study Technology Report* indicates that the *annual copper production of 109 million lb and annual gold production of 99,000 ounces* can be viewed as relatively accurate data.[16]

For our study, we set the production target at 109 million pounds of copper and 99,000 ounces of gold, so the copper and gold production constraints were:

$$0.267\% \times 2204.62 \times M \geq 109,000,000 \ (unit : pound)$$
$$0.170 \div 28.3495 \times M \geq 99,000 \ (unit : ounce)$$

That is,

$$5.886M \geq 109,000,000 \ (unit : pound)$$
$$0.00599658M \geq 99,000 \ (unit : ounce)$$

In its *Feasibility Study Report*, Ajax is designed to process a nominal 21,900,000 t/a, thus we have the functional constraint of total tonnes to mill:

$$M \geq 21,900,000 \ \ (unit: t)$$

According to the three inequalities above, the constraint that really matters is the functional constraint of total tonnes to mill:

$$\begin{cases} 5.886M \geq 109,000,000 \ \ (unit: pound) \\ 0.00599658M \geq 99,000 \ \ (unit: ounce) \\ M \geq 21,900,000 \ \ (unit: t) \end{cases} \Rightarrow M \geq 21,900,000 \ \ (unit: t)$$

3.5 Profit

3.5.1 Sales Revenue

The prices of copper and gold can be variable depending on the spot price or option price:

- Mineral Resources are reported using a **copper price of US $2.88/lb** and **a gold price of US$1,200/oz**.[17]
- Mineral Reserves are estimated by using a cut-off of US$4.53/t NSR, **a copper price of US$2.50/lb**, and a **gold price of US$1,085/oz.** [17]
- In Ajax's *Feasibility Study Technology Report*, **the copper price used is US$2.75/lb and the gold price is US$1,085/oz** with the exchange rate US$0.92:Cdn$1.00. (Note: This is the metal price used in the financial analysis of the Ajax Project prepared by Wardrop.) [16]

There have recently been major corrections in the commodity market due to a world-wide economic slow-down. It is our opinion that the forecasting used in these reports is a bit over-optimistic, and we would select the recent one-month average price (September 2015) as the coefficient for copper and gold in revenue equation: **copper price of US $2.40/lb** and **gold price of US$1,100/oz.**

Therefore, the revenue equation is:

$$5.886M \times 2.40 + 0.00599658M \times 1100 = 14.1264M + 6.596238M$$

3.5.2 Tax

Based on economic data and assumptions in the Ajax Project's *Feasibility Study*, it is estimated that over the course of construction and projected 23-year mine life, the Ajax Project will contribute up to **$550 million dollars** in federal and provincial taxes, **$210 million** in British Columbia Mining Act tax, and **$110 million** in municipal taxes.[16]

$$T_{federal\,\&\,provincial} = 550,000,000 \div 23 = 23,913,000$$
$$T_{BC\ Mining\ Act} = 210,000,000 \div 23 = 9,130,000$$
$$T_{Municipal} = 110,000,000 \div 23 = 4,782,000$$

Based on the proposed tax costs for Ajax, we can calculate tax dollars per tonne mined:

$$T_{tax} = (23,913,000 + 9,130,000 + 4,782,000) \div (60,000 \times 365) = 1.727 US\$ / t$$

3.5.3 Smelter Costs

The final products of the Ajax mine will be copper concentrate of 25% Cu containing approximately 18 g/t Au. The copper concentrate will be delivered to a smelter to process to obtain marketable metals. Based on Table 22.2 in [16], for 23 LOM the total cost for treatment, smelting, refining, and possible penalty is US$491,596,000 and the total cost for transportation, insurance, and representation is US$523,633,000. With total tonnes to mill 503,012,000 t, the cost for this portion per annum is

$$T_{smelter} = (491,596,000 + 523,633,000) \div 503,012,000 = 2.018 US\$ / t$$

3.5.4 Operating Costs

The *Ajax Report* indicates that operating costs are:

Table 3.2 Operating Cost Summary[16]

Description	Operating Costs (US$/t Milled)
Mining & In-Pit Crushing (AMEC)	4.48*
Processing (Including Labour) Cost (cf. Wardrop)	3.15
General and Admin (G&A)	0.53
Tailings (cf. Golder)	0.31
Operating Costs Total	**8.47**

*Note: The cost of US$4.48/t milled is equivalent to US$1.32/t mined

The Note on the figure shows that US$ 4.48/t milled is equivalent to US$ 1.32/t mined, since the Ajax overall stripping ratio (i.e., waste vs ore) is 2.4:1 and $4.48 \div (2.4 + 1) = 1.32$, so the total operating cost per tonne mined is:

$$8.47 \div (2.4 + 1) = 2.4912 US\$ / t$$

However, mining & in-pit crushing cost details are shown as the following:

Table 3.3 Mine Section Operating Costs for Ajax[16]

Operating Costs	Total	Mined ($/t)
Admin/ Overhead	159,594,531	0.11
Loading	188,552,137	0.11
Hauling	1,055,978,642	0.62
Drilling	161,525,069	0.09
Explosives	227,353,080	0.13
Support	141,575,992	0.08
Ancillary	40,144,184	0.02
Dewatering Allowance	28,093,378	0.01
Material Handling	249,605,029	0.15
Total	**2,252,422,043**	1.32

We consider the hauling, drilling and explosives costs as variable costs, and removed these three items from the operating costs, thus the fixed operating cost per tonne mined is:

$$E_{operating\ cost} = 2.4912 - (0.62 + 0.09 + 0.13) = 1.6512\, US\$ / t$$

Or equivalently, the fixed operating cost per tonne milled is:

$$E_{operating\ cost} = 1.6512 \times (2.4 + 1) = 5.614\, US\$ / t$$

3.5.5 Unit Hydro-Electric Cost

In the Power and Supplies section of the *Feasibility Study Technology Report*, the power cost is listed as follows:

Table 3.4 Power Supply Required for Process[16]

Plant Power	56,924 kW running			
Administration Buildings	238 kW running			
Supplies	**kWh/year**	**Unit Cost (US$/kWh)**	**Total Cost (US$/year)**	**Unit Cost (US$/t Ore)**
Plant Power	470,538,348	0.035	16,450,021	0.75
Total Plant Power Supply	**470,538,348**	**0.035**	**16,450,021**	**0.75**
G&A Power Supply	**1,408,109**	**0.035**	**49,227**	**0.002**

Table 3.5 Maintenance and Supply Costs[16]

Area	Total Cost (US$/year)	Unit Cost (US$/t Ore)
Cone Crusher and Related Equipment	920,000	0.0420
HPGR Crusher	920,000	0.0420
Grinding Area	2,300,000	0.1050
Flotation Area	2,760,000	0.1260
Concentrate Dewatering	920,000	0.0420
Reagents	230,000	0.0105
Assaying	138,000	0.0063
Miscellaneous Mill Supplies	460,000	0.0210
Misc. Building Complex Supplies	460,000	0.0210
Total Maintenance Supplies	**9,108,000**	**0.416**

Through calculation, the hydro-electric rate for unit raw ore is US$1.168/t per tonne milled:

$$\gamma_{hydro} = 0.75 + 0.002 + 0.416 = 1.168 US\$ / t$$

3.5.6 Drilling Cost

According to the "Disadvantages to Wet Drilling" section in the *Dust Handbook for Industrial Mineral Mining and Processing*, the use of water degrades the tri-cone roller drill bits and shortens their lives by 50 percent or more.[1]

We assume that the wet drilling method would thus double the cost.

The Ajax capital costs for the mining function are showed as the following,[12] where equipment costs are for **one year**:

Table 3.6 Mine Capital Cost

Area	Cost (US$)
Pre-stripping	34,443,000
Drilling Equipment	9,969,000
Loading Equipment	81,338,000
Hauling Equipment	181,418,000
Support Equipment	29,953,000
Mine Maintenance Equipment	13,608,000
Dewatering	3,609,000
Crushing	81,600,000
Conveying	84,822,000
Stacking	54,910,000
Crushing – Sustaining	8,000,000
Stacking – Sustaining	1,200,000
Engineering Equipment	6,655,000

From [16], we learn that the requirement for drilling equipment are as follows during the proposed 23-year Life-of-Mine (LOM).

Table 3.7 Drilling Equipment during 23-years LOM[16]

Year	Equipment Requirement	Year	Equipment Requirement
1 (Q1-Q4)	3-3-3-4	13	4
2(Q1-Q4)	3-4-4-4	14	4
3(Q1-Q4)	4-4-4-4	15	4
4(Q1-Q4)	4-4-4-4	16	4
5(Q1-Q4)	4-4-4-4	17	3
6	4	18	3

7	4	19	3
8	4	20	3
9	4	21	2
10	4	22	-
11	4	23	-
12	4		

Form the table, we see that the equipment requirement for every year has a little change, so it is appropriate to assume the annual cost for drilling is US$9,969,000.

The proposed mine plan envisages a conventional open pit operation producing 60,000 t/day and the drilling equipment cost is 0.09 US$/t.[12]

The calculation for drilling cost coefficients is shown as the following:

Dry drilling with dust collection: $\gamma_{11} = \frac{9,969,000}{60,000 \times 365} + 0.09 = 0.5452\$US/t$

Wet drilling: $\gamma_{12} = \frac{9,969,000}{60,000 \times 365} \times 150\% + 0.09 = 0.7728\$US/t$

3.5.7 Blasting Costs

The Malartic 2014 report (Table 3.3, Reference mining cost per tonne mined (in US $)) shows the unit cost for blasting of different diameters.[13]

Table 3.8 Blasting Cost

Diameter	89mm	140mm	216mm
Unit cost (US$/t)	1.891	0.936	0.700

Using the linear regression method, we have created the following prediction model:

$$y = -0.0089x + 2.4946$$

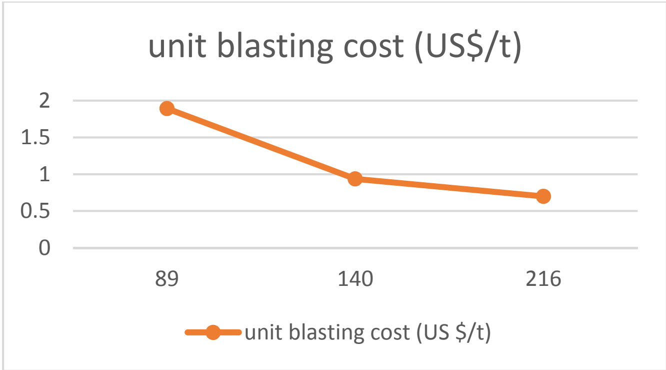

Figure 3.1 Unit Blasting Cost

Blast-hole drilling at the proposed Ajax mine will be performed with nominal 270 mm (10 5/8") diameter production drills.[16] The unit cost for blasting in Ajax would thus be:

$$\gamma_{21} = unit\ cost = -0.0089 \times 270 + 2.4946 = 0.0916\$US/t$$

The cost for blasting using water cartridges cannot be found in the literature. The method requires the insertion of a properly sized plastic bag prefilled with water into the blasting hole. We estimate this cost based on the 50% extra cost assumption, which yields the wet explosion cost US$0.13/t. Since Ajax promises to take dust control measures in blasting, we would assume the unit blasting cost with water cartridges to be US$0.13/t.

3.5.8 Hauling Cost

The three hauling methods (no watering, level 1 watering and level 2 watering) are distinct in the prediction of water usage. The following is the information obtained:

From the feasibility study, the cost for hauling would be US$ 0.62/t.

The haul road is 2.9km*12m. The calculation is as follows:

- If level 1 is chosen, then 2L/m^2/h is taken: 2,900*12*2=69,600L/h=69.6m^3/h
- If level 2 is chosen, then more than 2L/m^2/h is taken : more than 2,900*12*2=69,600L/h=69.6m^3/h
- If no watering method is chosen, then there will be no water usage.

Since the water is to be taken from Kamloops Lake or recycled from tailings ponds, and the water cost is not mentioned in the Ajax report, the labour expenditure is considered to be the main cost. We assume the cost rate of no watering, level 1 watering and level 2 watering are 100%, 115% and 120%, respectively. Thus

$$\gamma_{41} = \$US\,0.62$$
$$\gamma_{42} = 115\% \times 0.62 = \$US\,0.7130$$
$$\gamma_{43} = 120\% \times 0.62 = \$US\,0.7440$$

3.5.9 Target of Profit

The initial capital cost for the Ajax Project is estimated to be US$795 million. Without considering interest expenses and depreciation factor, we take 15% Return on Investment (ROI) on initial investment as the annual profit target. So the target profit is:

$$T_{profit} = 795 \times 0.15 = 119.25US\$(million)$$

3.5.10 Summary of Profit Equation

The profit equation now looks like:

$$\begin{aligned}
&\underset{copper}{16.9517M} + \underset{gold}{7.1959M} - \underset{hydro}{T_{initial}} - [1.168 + \underset{drilling}{(0.5452 \cdot \beta_{11} + 0.7728 \cdot \beta_{12})} + \underset{blasting}{(0.0916\beta_{21} + 0.130\beta_{22})} + \underset{hauling}{(0.62\beta_{41} + 0.7130\beta_{42} + 0.744\beta_{43})} + \underset{operating}{1.6512]M} \\
&-[T_{tax} + T_{smelter}]M \\
&= 16.9517M + 7.1959M - 34.565 - [1.168 + (0.5452 \cdot \beta_{11} + 0.7728 \cdot \beta_{12}) + (0.0916\beta_{21} + 0.130\beta_{22}) + (0.62\beta_{41} + 0.7130\beta_{42} + 0.744\beta_{43}) + 1.6512]M \\
&-[1.727 + 2.018]M \\
&= 119,250,000 + d^+_{profit} - d^-_{profit}
\end{aligned}$$

4. Computation

4.1 Mathematical Model

With data from the previous sections, now the goal programming model becomes:

$$\min \quad P_1 d^-_{profit} + P_2(d^+_{Air} + d^+_{waste\,water})$$

$$s.t.$$

$$\begin{cases}
14.126M + 6.596238M - [(0.5452 \cdot \beta_{11} + 0.7728 \cdot \beta_{12}) + (0.0916\beta_{21} + 0.130\beta_{22}) \\
+(0.62\beta_{41} + 0.7130\beta_{42} + 0.744\beta_{43}) + 6.5642]M = 153,815,000 + d^+_{profit} - d^-_{profit} \\
(2.7241\beta_{21} + 0.4402\beta_{22})M + (72.5\beta_{31} + 36.25\beta_{32})M + 22M + (6\beta_{41} + 3\beta_{42})M \\
= 2,093,000,000 + d^+_{air} - d^-_{air} \quad (unit: g) \\
0.1986M = 4,310,568 + d^+_{wastewater} - d^-_{wastewater} \quad (Unit: g) \\
M \geq 21,900,000 \quad (unit: t)
\end{cases}$$

After rescaling the coefficients in the model, the unit of M is changed from ton to 10^6 ton and the data on the right-hand side is also compressed to $\frac{1}{10^6}$ of the original data.

Furthermore, due to the difference between the units and measurements of d^-_{profit}, d^+_{Air}, $d^+_{waste\,water}$ and $d^-_{recycled\ water}$, standardization becomes necessary.

The modified model now looks like:

$$\min \quad P_1 \frac{d^-_{profit}}{153.615} + P_2 \left(\frac{d^+_{Air}}{2093} + \frac{d^+_{waste\,water}}{4.310568}\right)$$

$$s.t.$$

$$\begin{cases} 14.126M + 6.596238M - [(0.5452 \cdot \beta_{11} + 0.7728 \cdot \beta_{12}) + (0.0916\beta_{21} + 0.130\beta_{22}) \\ +(0.62\beta_{41} + 0.7130\beta_{42} + 0.744\beta_{43}) + 6.5642]M = 153.815 + d^+_{profit} - d^-_{profit} \\ (2.7241\beta_{21} + 0.4402\beta_{22})M + (72.5\beta_{31} + 36.25\beta_{32})M + 22M + (6\beta_{41} + 3\beta_{42})M \\ = 2{,}093 + d^+_{air} - d^-_{air} \\ 0.1986M = 4.310568 + d^+_{wastewater} - d^-_{wastewater} \\ M \geq 21.9 \end{cases}$$

Here, P_1 represents the first level optimization in which we maximize the profit of the project and P_2 represents the second level optimization in which we minimize the amount of air emission and waste water released.

4.2 Lingo Codes

We use an optimization package, Lingo, to solve the balance model. The program codes of the two levels are shown below:

```
model:
sets:
var/1..3/:a,b,d,e;
endsets
data:
b = 2093,4.310568,153.815; !column vector of equation target;

c11=1; c12=0;
c21=1; c22=0;
c31=1; c32=0; c33=0;


f11=2.7241; f12=0.4402;
f21=72.5; f22=36.25;
f31=6; f32=3; f33=0; !coefficients of air equation;

g11=0.5452; g12=0.7728;
g21=0.0916; g22=0.13;
g31=0.62; g32=0.7130; g33=0.744;   !coefficients of profit equation;

enddata
a(1)=c11*f11+c12*f12+c21*f21+c22*f22+c31*f31+c32*f32+c33*f33+22;!final
air coefficient after determining the process methods;
a(2)=0.1986;!waste water coefficient;
a(3)=14.158038-
(c11*g11+c12*g12+c21*g21+c22*g22+c31*g31+c32*g32+c33*g33);!final profit
coefficient after determining the process methods;
!gold production coefficient;
x>=21.9;
```

```
[OBJ]min=(1/153.815)*d(3);
@for(var(i):a(i)*x=b(i)-d(i)+e(i););
end
```

Figure 4.1 Program Code for the First Level of Scenario 1

```
model:
sets:
var/1..3/:a,b,d,e;
endsets
data:
b = 2093,4.310568,153.815; !column vector of equation target;

c11=1; c12=0;
c21=1; c22=0;
c31=1; c32=0; c33=0;


f11=2.7241; f12=0.4402;
f21=72.5; f22=36.25;
f31=6; f32=3; f33=0; !coefficients of air equation;

g11=0.5452; g12=0.7728;
g21=0.0916; g22=0.13;
g31=0.62; g32=0.7130; g33=0.744;   !coefficients of profit equation;

enddata
a(1)=c11*f11+c12*f12+c21*f21+c22*f22+c31*f31+c32*f32+c33*f33+22;!final
air coefficient after determining the process methods;
a(2)=0.1986;!waste water coefficient;
a(3)=14.158038-
(c11*g11+c12*g12+c21*g21+c22*g22+c31*g31+c32*g32+c33*g33);!final profit
coefficient after determining the process methods;
x>=21.9;
[OBJ]min=(1/2093)*e(1)+(1/4.310568)*e(2);
d(3)=0;
@for(var(i):a(i)*x=b(i)-d(i)+e(i););
end
```

Figure 4.2 Program Code for the Second Level of Scenario 1

4.3 Output

Different methods for each of the three processes generate different outputs. There are two methods in the drilling process, two in the blasting process and three in the hauling process, so there are twelve possible scenarios to be discussed.

Table 4.1 Scenario Table

Scenario Number	Drilling Method		Blasting Method		Hauling Method		
	Dry drilling with dust control	Wet drilling	Blasting without watering	Blasting with water cartridges	Level 1 Watering (2 litres/m2/h)	Level 2 Watering (>2 litres/m2/h)	Sealed or Salt-Encrusted Roads

1	✓		✓		✓		
2	✓		✓			✓	
3	✓		✓				✓
4	✓			✓	✓		
5	✓			✓		✓	
6	✓			✓			✓
7		✓	✓		✓		
8		✓	✓			✓	
9		✓	✓				✓
10		✓		✓	✓		
11		✓		✓		✓	
12		✓		✓			✓

Taking the first scenario as an example, all the methods are the cheapest with the worst impact on environment (outputs presented below).

The first deviation d^{+}_{profit} (D(3) in the Lingo codes) is zero.

```
Global optimal solution found.
Objective value:                              0.000000
Infeasibilities:                              0.000000
Total solver iterations:                             0


                       Variable           Value        Reduced Cost
                            C11        1.000000            0.000000
                            C12        0.000000            0.000000
                            C21        1.000000            0.000000
                            C22        0.000000            0.000000
                            C31        1.000000            0.000000
                            C32        0.000000            0.000000
                            C33        0.000000            0.000000
                            F11        2.724100            0.000000
                            F12       0.4402000            0.000000
                            F21        72.50000            0.000000
                            F22        36.25000            0.000000
                            F31        6.000000            0.000000
                            F32        3.000000            0.000000
                            F33        0.000000            0.000000
                            G11       0.5452000            0.000000
                            G12       0.7728000            0.000000
                            G21       0.9160000E-01        0.000000
                            G22       0.1300000            0.000000
                            G31       0.6200000            0.000000
                            G32       0.7130000            0.000000
                            G33       0.7440000            0.000000
                              X        21.90000            0.000000
                          A( 1)        103.2241            0.000000
                          A( 2)       0.1986000            0.000000
                          A( 3)        12.90124            0.000000
                          B( 1)        2093.000            0.000000
                          B( 2)        4.310568            0.000000
                          B( 3)        153.8150            0.000000
```

```
           D( 1)        0.000000            0.000000
           D( 2)        0.000000            0.000000
           D( 3)        0.000000          0.6501317E-02
           E( 1)        167.6078            0.000000
           E( 2)      0.3877200E-01         0.000000
           E( 3)        128.7221            0.000000

             Row    Slack or Surplus      Dual Price
               1        0.000000            0.000000
               2        0.000000            0.000000
               3        0.000000            0.000000
               4        0.000000            0.000000
             OBJ        0.000000           -1.000000
               6        0.000000            0.000000
               7        0.000000            0.000000
               8        0.000000            0.000000
```

Figure 4.3 Output of the First Level of Scenario 1

```
Global optimal solution found.
Objective value:                             0.8907481E-01
Infeasibilities:                              0.000000
Total solver iterations:                             0


                        Variable           Value        Reduced Cost
                             C11        1.000000            0.000000
                             C12        0.000000            0.000000
                             C21        1.000000            0.000000
                             C22        0.000000            0.000000
                             C31        1.000000            0.000000
                             C32        0.000000            0.000000
                             C33        0.000000            0.000000
                             F11        2.724100            0.000000
                             F12       0.4402000            0.000000
                             F21        72.50000            0.000000
                             F22        36.25000            0.000000
                             F31        6.000000            0.000000
                             F32        3.000000            0.000000
                             F33        0.000000            0.000000
                             G11       0.5452000            0.000000
                             G12       0.7728000            0.000000
                             G21      0.9160000E-01         0.000000
                             G22       0.1300000            0.000000
                             G31       0.6200000            0.000000
                             G32       0.7130000            0.000000
                             G33       0.7440000            0.000000
                               X        21.90000            0.000000
                           A( 1)        103.2241            0.000000
                           A( 2)       0.1986000            0.000000
                           A( 3)        12.90124            0.000000
                           B( 1)        2093.000            0.000000
                           B( 2)        4.310568            0.000000
                           B( 3)        153.8150            0.000000
                           D( 1)        0.000000          0.4777831E-03
                           D( 2)        0.000000           0.2319880
```

```
D( 3)        0.000000           0.000000
E( 1)        167.6078           0.000000
E( 2)        0.3877200E-01      0.000000
E( 3)        128.7221           0.000000

  Row    Slack or Surplus      Dual Price
    1        0.000000        -0.1046345E-01
    2        0.000000         -5.080537
    3        0.000000          0.000000
    4        0.000000        -0.9539154E-01
  OBJ      0.8907481E-01      -1.000000
    6        0.000000          0.000000
    7        0.000000         0.4777831E-03
    8        0.000000         0.2319880
    9        0.000000          0.000000
```

Figure 4.4 Output of the Second Level of Scenario 1

The output of the second level shows that optimal annual ore to mill is 21.9 million tonnes, and the profit exceeds US$128.7221 million than the target profit, PM10 emission exceeds the target by 167.60 tonnes, the waste water exceeds the target by 38,772 cubic metres.

Thus, in the first scenario, the optimal total amount of ore to mill is 21.9 million tonnes. In this case, the profit is US$247.972 million, discharged waste water is 4.34934 million cubic metres and PM10 emission is 2260.60 tonnes. The solutions of the twelve scenarios are given in the following table:

Table 4.2 Solutions of 12 Scenarios of Balance Model

Scenario	Total tonnes to mill (M) (Unit: 10^6 t)	Profit (Unit:10^6 US$)	Discharge Waste Water (Unit:10^6 m^3)	PM10 Emission (Unit:10^6 g)	First Deviation
1	21.9	247.972 (Exceed by 107.94%)	4.34934 (Exceed by 0.89%)	2260.61 (Exceed by 8.01%)	0
2	21.9	245.93 (Exceed by 106.23%)	4.34934 (Exceed by 0.89%)	2194.91 (Exceed by 4.87%)	0
3	21.9	247.25 (Exceed by 105.66%)	4.34934 (Exceed by 0.89%)	2129.208 (Exceed by 1.73%)	0
4	21.9	247.13 (Exceed by 107.23%)	4.34934 (Exceed by 0.89%)	1466.73 (Fall short by 29.92%)	0
5	21.9	245.09 (Exceed by 105.53%)	4.34934 (Exceed by 0.89%)	1401.03 (Fall short by 33.06%)	0
6	21.9	244.45 (Exceed by 104.96%)	4.34934 (Exceed by 0.89%)	1335.333 (Fall short by 36.20%)	0
7	21.9	242.98 (Exceed by 103.76%)	4.34934 (Exceed by 0.89%)	2210.59 (Exceed by 5.61%)	0

8	21.9	240.95 (Exceed by 102.055%)	4.34934 (Exceed by 0.89%)	4144.89 (Exceed by 2.48%)	0
9	21.9	240.27 (Exceed by 101.48%)	4.34934 (Exceed by 0.89%)	2079.190 (Fall short by 0.66%)	0
10	21.9	242.15 (Exceed by 103.05%)	4.34934 (Exceed by 0.89%)	1416.72 (Fall short by 32.31%)	0
11	21.9	240.11 (Exceed by 101.35%)	4.34934 (Exceed by 0.89%)	1351.02 (Fall short by 35.45%)	0
12	21.9	239.43 (Exceed by 100.78%)	4.34934 (Exceed by 0.89%)	1285.315 (Fall short by 38.59%)	0

The most environmental-friendly scenario is that of number 12: profit is US$239.43 million, discharged waste water is 4.34934 million cubic metres and PM10 emissions are 1285.315 tonnes.

5. Analysis

5.1 Analysis of the Balance Model

To demonstrate better results, the scatter diagram of the profit and air emission is shown:

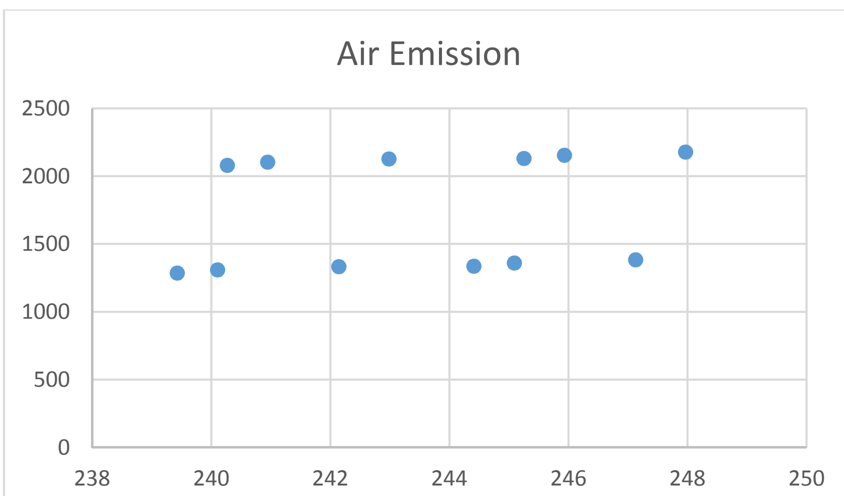

Figure 5.1 Profit vs Air Emissions

From the plotting, we can make the following observations:

- In Scenario 1 (dry drilling with dust control, blasting without water cartridges and level 1 watering in hauling) the profit is the largest (US$247.972 million), but also produces the greatest level of dust emissions (2260.61 tonnes). Scenario 12 (wet drilling, blasting with water cartridges and best hauling method) has the least impact regarding air pollution with dust emissions of 1285.315 tonnes, but also generates the lowest profit (US$239.43 million).

- The plotted points in Figure 5.1 are clearly divided into two groups: one group contains the Scenarios of 1,2,3,7,8,9, while the other group contains the points 4,5,6,10,11,12.
  For each group, the trend of the points shows that there is a positive correlation between profit and air emissions. Thus, the more money spent on environmental management, the less profit.
- Comparison of the two groups shows that group one causes heaver air pollution than group two. From the Scenario Table 4.1, the distinction between these two groups is the **method for blasting.** The scenarios in group one use blasting without water cartridges and generate more dust, while the scenarios in group two use blasting with water cartridges and have less dust emissions. **The methods of blasting have a great impact on the result of the model.** The air emissions and the costs in the three mining processes of drilling, blasting and hauling are shown in Table 5.1 and Figure 5.2.
  Comparisons of the cost of reducing dust emissions in each process, show that the highest is the drilling of US$ 0.0996541/g, and the lowest is the blasting of US$ 0.00105931/g. Another crucial reason for the great impact of blasting is that the blasting coefficients are large, almost hundreds and thousands of times greater than the drilling and hauling coefficients.

Table 5.1 Cost for Reducing Air Emission

Mining Process		Air Emission (g/t)	Unit Cost (US$/t)	Cost for per gram air emission reduced
Drilling	Dry with dust control	2.7241	0.5452	US$ 0.0996541/g
	Wet	0.4402	0.7728	
Blasting	Without water cartridges	72.5	0.0916	US$ 0.00105931/g
	With water cartridges	36.25	0.130	
Hauling	Level 1 (2 L/m2/h)	3	0.62	US$ 0.02883721/g
	Level 2 (>2 L/m2/h)	6	0.7130	
	Sealed or salt-encrusted roads	0	0.744	

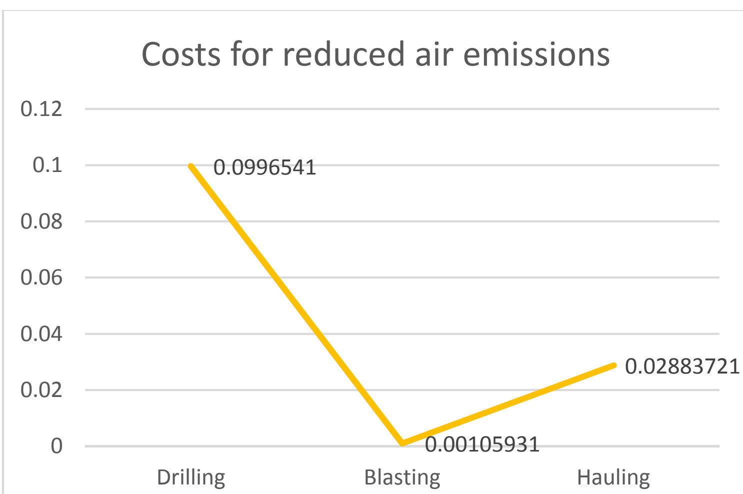

Figure 5.2 Costs for Reduced Air Emissions

5.2 Variation of the Priorities

Let the first priority be the environmental impact and the second priority be the economic profit. In a re-run of Lingo, we found that for the first scenario the total tonnes to mill are 21.9 million tonnes, the profit is US$247.97 million, the discharge waste water is 4.34934 million cubic metres and the air emissions are 2260.60 million grams. That is, the solution is identical to the other priority order.

For all twelve scenarios, the change of the priority order has not resulted in any changes to the optimal solutions, which indicates that **the stability of the balance model is good** since regardless of how we set the order of priorities, i.e., environmental goal or economic goal as the first priority, the results are the same.

5.3 Sensitive Analysis of Cost of Blasting under Dust Control

In the data collection with the unit cost of blasting, **the cost in blasting with water cartridges (γ_{22}) is assumed to be US$ 0.13/t, the same as the explosion cost in the *Ajax Feasibility Report***. Since the cost of blasting may be influenced by many factors, such as the cost of the cartridges, salary of the workers, etc., it is important to analyze the impact from the cost of blasting. We take the fourth scenario (dry drilling with dust control, blasting with water cartridges and hauling with the first level watering) as an example. Tthe sensitive analysis of the unit cost for blasting with water cartridges is given below:

Table 5.2 Sensitive Analysis of Cost of Blasting under Dust Control (γ_{22}) for 4th Scenario

Changing of the cost	Total tonnes to mill (M) (Unit: 10^6)	Profit (Unit: 10^6 US$)
-20% (US$0.104/t)	21.9	247.7000
-10% (US$0.117/t)	21.9	247.4159
0 (US$0.13/t)	21.9	247.1312
+10% (US$0.143/t)	21.9	246.8465
+20% (US$0.156/t)	21.9	246.5618

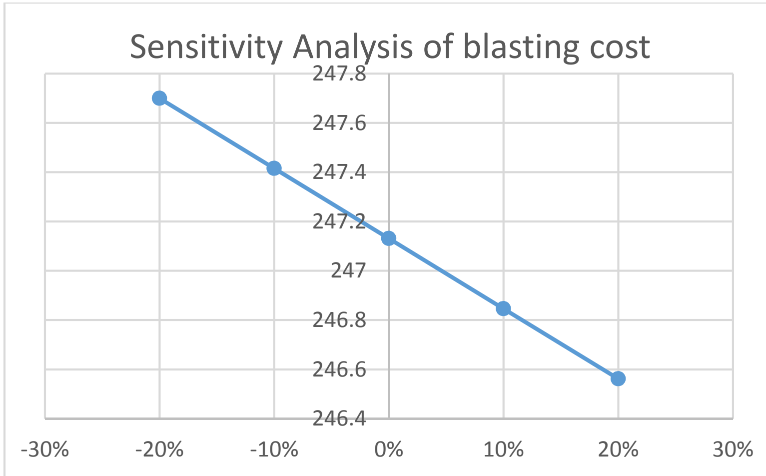

Figure 5.3 Sensitive Analysis of Blasting Cost γ_{22} for 4th Scenario

Clearly, the profit is a linear function of the change in the cost of blasting with slope -0.2847. That is, each 10% of increase (res. of decrease) in cost of blasting will decrease (or increase) the total profit by US$0.2847 million.

5.4 Sensitive Analysis of Metal Price

Sensitive analysis of the first scenario (drilling, blasting and hauling methods are the cheapest) with the change of copper and gold price was conducted.

- Original result

Table 5.3 Original Result for the Scenario 1

Scenario	Total tones to mill (M) (Unit:10^6 t)	Profit (Unit:10^6 US$)	Discharge Waste Water (Unit:10^6 m^3)	Air Emission (Unit:10^6 g)
1	21.9	247.972 (Exceed by 107.94%)	4.34934 (Exceed by 0.89%)	2260.61 (Exceed by 8.01%)

- Sensitive Analysis for Copper Price

Let the copper price change with range of 10% and 20%.

Table 5.4 Result with Change of Copper Price in Scenario 1

Changing rate of the copper price	Total tonnes to mill (M) (Unit:10^6 t)	Profit (Unit: million US$)
-20% (US$1.92/lb)	21.9	186.1616
-10% (US$2.16/lb)	21.9	217.0668

0 (US $2.40/lb)	21.9	247.972
+10% (US$2.64/lb)	21.9	278.8774
+20% (US$2.88/lb)	21.9	309.7827

- Sensitive Analysis for Gold Price

Let the gold price change with a range of 10% and 20%.

Table 5.5 Result with Change of Gold Price in Scenario 1

Changing rate of the gold price	Total tonnes to mill (M) (Unit: 10^6 t)	Profit (Unit: Million US$)
-20% (US$880/oz)	21.9	219.0806
-10% (US$990/oz)	21.9	233.5264
0 (US$1,100/oz)	21.9	247.972
+10% (US$1,210/oz)	21.9	262.4179
+20% (US$1,320/oz)	21.9	276.8637

- Sensitive Comparison of of Metals

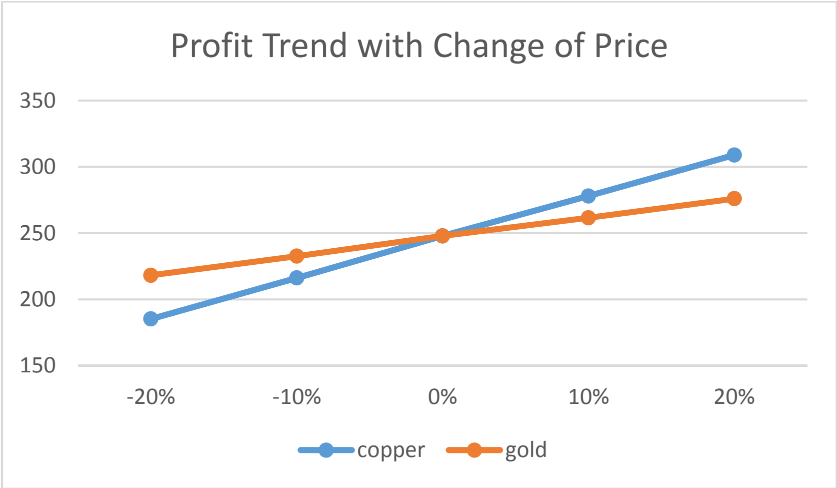

Figure 5.4 Sensitive Analysis of Metal Prices

Clearly, Ajax's profit will increase (or decrease) with respect to the increase of metal prices. Moreover, **Ajax's bottom line is more sensitive to the volatility of copper prices than gold prices.**

5.5 Rising Standard of Dust Control

In the data collection, the air emission target was set at 40% of Highland Valley Copper's. However, HVC is approximately 80 kilometers away from Kamloops while the proposed Ajax mine would be only a few kilometers away from the community.[18] Observing the amount of dustfall within the three kilometre radius of the HVC mine site, it is clear that 40% of dust accumulation will not be bearable for the residents of the community. Even if 20% of HVC's PM10 emissions would be tolerable or not is in question. For this analysis, we adjust the standard of PM10 emissions from the proposed Ajax Mine to be 20% of HVC's PM10 emission (1,046.5 tonnes) as an investigation point. Taking the most environmental-friendly scenario--the 12th scenario--as an example, the comparison of the higher-standard and the original models is shown below:

Table 5.6 Comparison of the Higher-standard and the Original Models

	Scenario	Total tonnes to mill (M) (Unit: 10^6 t)	Profit (Unit: 10^6 US$)	Air Emission (Unit: 10^6 g)
Original Model	12	21.9	239.4311 (Exceed by 100.78%)	1285.315 (Fall short by 38.59%)
High-Standard Model	12	21.9	239.4311 (Exceed by 100.78%)	1285.315 (Exceed by 22.76%)

As the PM10 emission standard rises to 20% of HVC's, the PM10 emission exceeds the target by 22.76% instead of falling short of 38.59%. **This could be a major challenge to Ajax since even with all dust-control measurements discussed in place, PM10 emissions still exceed the target by 22.76%.**

6. Major Findings and Future Investigation

6.1 Major Findings

Our aim was to find the most efficient way to operate the Ajax Mine so that the maximum economic profit and the minimal impact to the environment and health could be achieved. The major findings are:

- The optimal amount to mill per year is 21.9 million tonnes.
- With the different methods taken in the different processes, the profit varies. Generally speaking, when the profit is greater, then the air emissions will increase. Moreover, improved blasting technique is the most cost-effective strategy to reduce pollutants since the cost to reduce air emissions associated with blasting is the lowest.
- The order of priorities for economic profit or environmental protection is unimportant in this balance model, because the outcomes for different priority orders are identical, which implies that the balance model is fairly stable.
- When the cost of blasting increases, the total profit decreases proportionally.
- **With a low environmental standard (i.e., 40% of HVC PM10 emission), the proposed Ajax mine would be able to meet the targets of discharged waste water and air emissions and have a**

healthy investment return (exceed the financial target by more than 100%). Moreover, Ajax's profit is more sensitive to the price change of copper than that of gold.

- If the target for air emissions is raised (e.g., 20% of HVC PM10 emission), Ajax fails to meet the target of 1,046.5 tonnes PM10 (exceed by 22.76%) even using the all three best dust-control methods available. **Therefore, with the higher environmental standard, the three dust-control methods studied in this project, in addition to covering the crushed ore stockpile completely, will be insufficient and other new technologies or more effective dust-control methods would be required to be adopted in the Ajax operation to meet the higher target.**

6.2 Future Investigation

Due to the short duration of the current project, we had to limit the scope and breadth of the investigation. We also left some of components out of the balance model due to lack of data or requirement of robustness of the model. If the data is available or more time is permitted, we could expand the model in four different directions:

6.2.1 Impact of Wind on Air Emissions

The short distance between Ajax mine and the community makes wind a crucial factor when air emissions are taken into consideration, since the wind can carry a large amount of dust to the city. Based on the locations of Ajax Mine and Aberdeen area, usually only Southwest (SW), West-Southwest (WSW), and South-Southwest (SSW) winds have impact on the transportation of air pollutants from Ajax Mine to the city. The air emissions constraint can be modified with the wind factor added.

✧ The Original Air Emissions Equation

$$\underbrace{(\beta_{11}\alpha_{11}+\beta_{12}\alpha_{12})M}_{drilling}+\underbrace{(\beta_{21}\alpha_{21}+\beta_{22}\alpha_{22})M}_{blasting}+\underbrace{\alpha_3 M}_{loading}+\underbrace{(\beta_{41}\alpha_{41}+\beta_{42}\alpha_{42}+\beta_{43}\alpha_{43})M}_{hauling}=T_{air}+d_{air}^{+}-d_{air}^{-}$$

✧ New Air Emissions Equation with Wind Factor

$$\underbrace{(c_1T_1+c_2T_2+c_3T_3)}_{wind\ factor}[\underbrace{(\beta_{11}\alpha_{11}+\beta_{12}\alpha_{12})}_{drilling}+\underbrace{(\beta_{21}\alpha_{21}+\beta_{22}\alpha_{22})}_{blasting}+\underbrace{\alpha_3}_{loading}+\underbrace{(\beta_{41}\alpha_{41}+\beta_{42}\alpha_{42}+\beta_{43}\alpha_{43})}_{hauling}]M=T_{air}+d_{air}^{+}-d_{air}^{-}$$

where c_1 is the probability of a gentle wind of SW, WSW and SSW; c_2 is the probability of the medium wind of SW, WSW and SSW; c_3 is the probability of the strong wind of SW, WSW and SSW; T_1 is the amount of dust brought by a gentle wind of SW, WSW and WSW when one tonne of dust is produced; T_2 is the amount of dust brought by medium wind of SW, WSW and WSW when one tonne of dust is produced; T_3 is the amount of dust brought by strong wind of SW, WSW and WSW when one tonne of dust is produced.

6.2.2 Availability of Recycled Water Data

The original model includes recycled water, however in the computation model the recycled water was removed due to lack of data regarding recycled water. If such data becomes available, the recycled water can be put back into the calculation model. The required data is outlined in the following table.

Table 6.1 Required Data for Recycled Water

Methods of the Recycled Water	Recycled Rate	Unit Cost for Each Tonne Milled
Good	α_{61}	γ_{61}
Fair	α_{62}	γ_{62}
Poor	α_{63}	γ_{63}
Recycled Water Target	$T_{recycle\ water}$	

6.2.3 More Variables to be Considered

In the current model, there is only one variable M, the amount of ore to mill, while in the more realistic model, we would require more variables to describe the process. For example, we may need several variables to represent the amount of rock mined, the amount of waste rock, the amount of ore crushed, and the amount of ore milled, etc. There will be more constraints required to link these variable together. With the new variables and constraints, the model would characterize the process more accurately and also increase the computation time.

6.2.4 Multi-Year Dynamic Model

Our model was designed for the average situation of 23-year LOM. However, for each year, the productivity, the commodity price, the equipment investment and other expenses may vary. So we need a multi-year dynamic model to balance economic profit and environmental impact.

We could establish a sub-model for each year, and then combine the 23 sub-models to form a multi-year dynamic model linked by inventory variables. The illustration of the multi-year dynamic model is given below.

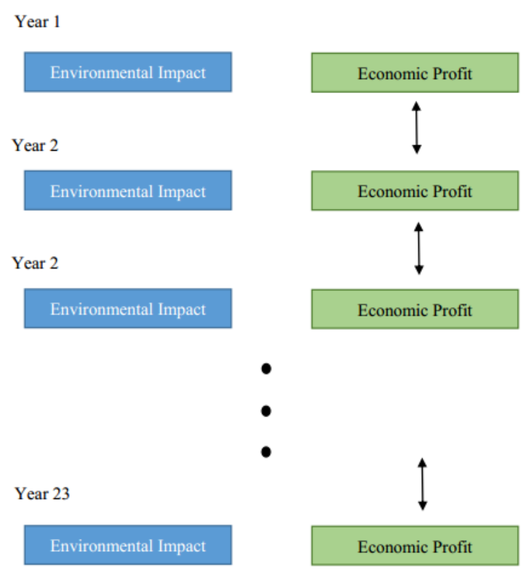

Figure 6.1 Illustration of Multi-Year Dynamic Model

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