Value of More Sophistication: Capital Investment Decision-Making with Competitive Dynamics in the Mining Industry

by

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Abstract

In many mining markets, one of the central business planning decisions faced by firms is where, when, and by how much to expand their production capacity. Appropriate investment planning methodology is important to both the mining industry and the wider economy. Currently, new mine investment decisions are most often based on the classic project evaluation methodology of discounted cash flow analysis (DCF) applied to the individual potential projects, which is flawed in its inadequate consideration of risk and flexibility, of impact on the profit of the firm, and of competitive dynamics in oligopoly markets.

More sophisticated methods that account for these complexities have been proposed in academic literature; however, their value in realistic market settings has been little demonstrated in past literature and they are rarely adopted in practice. This thesis compares four investment decision paradigms of increasing scope and complexity in a three-firm mineral commodity market, based primarily on the firm-level cash flow NPV outcome in Monte Carlo simulations of the market. The analysis is conducted for various market scenarios of different demand growth patterns, volatility, demand elasticity, and supply structure.

Simulation results show that in almost all scenarios, the game theoretic and option-based best-firm-NPV policies outperform the positive-mine-NPV policy substantially for all firms, regardless their market and cost position. However, the difference between the best-firm-NPV policy and the positive-firm-NPV policy is often small, depending on the scenario. Overall, the evaluation conducted in this thesis contributes to our understanding of how useful having more sophisticated investment decision methods might be to the firms and under what market conditions.

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Chapter 1 – Introduction

1.1 Motivation and Key Research Questions

In many mining markets, one of the central business planning decisions faced by firms is where, when, and by how much to expand their production capacity. In a recent analysis of the trends and business risks facing the mining and metals industry, Deloitte Energy & Resources indicates that capital allocation is the top strategic risk for the industry in 2010 (Deloitte & Touche, 2010). These investment decisions impact not only the market supply, price and the firms’ own profitability, but also the economics of the numerous manufacturing industries that rely on the commodities as raw materials. Hence, appropriate investment planning methodology is important to not only the mining industries themselves, but also the economy as a whole.

Currently, the investment decisions of mining firms are most often based on the classic project evaluation methodology of discounted cash flow analysis (DCF) applied to the individual prospective projects. Under the DCF, prospective cash flows of the mine investment are evaluated under average price expectations along with other risk considerations, and mines with a positive net present value of cash flow could be opened. There is no systematic consideration of the impact of opening a large mine on firm-level price and profit. Expected firm NPV, the widely accepted theoretically correct evaluation criterion for financial and industrial projects (Brealey, Myers, Sick, & Giammarino, 1992; Bussey, 1978; Hirschleifer, 1958), is not consistently or correctly calculated under uncertainties in the market and firm conditions. Furthermore, firms do not take into account the likely competitive responses of other market players when they evaluate expansion decisions, which might be important in oligopolistic markets. Partly due to these capital planning shortcomings, some commodity markets have been criticized as prone to over-expansion (Gait, Healer, & Didziulyte, 2013; Rees, 2013), which leads to price drops and profit erosion and contribute to the boom-and-bust cycle of the commodity market.

Besides noting these shortcomings, researchers have often suggested the integration of more advanced techniques, especially real option theory and game theory, into the capital planning
process of the firm. However, these techniques have been criticized as difficult to implement and marginal in their contribution to making better decisions.

This thesis aims to examine the firm and market behaviors that arise in a three-firm mineral commodity market when the firms use different types of investment decision paradigms under different market structures and conditions. Its key research question is whether and by how much more sophisticated capacity investment planning process improves relevant firm outcomes and under different market conditions.
Chapter 2 – The Mining Investment Decision Problem: Theory and Practice

2.1 The Need for Investment Planning in Mining Investment

One of the central questions in the mining industries is the selection and timing of investing in opening up new mines, as these investments would directly impact the production volume of not only the owner of the new mines, but the production capacity in the market and potentially the mineral price. In 2010, Deloitte Energy & Resources found in a survey and analysis of mineral producers that capital allocation is the top strategic risk for the mining industry (Deloitte & Touche, 2010). More recently, investment analysts heavily criticized potential large mines to open in the iron ore market for their potential to depress price and destroy value for the shareholders of the firms they belong to (Gait et al., 2013; Knights, 2013; Toyne, 2013).

Mining investment are distinct from investment projects in many other industries in that they are usually irreversible and fixed in size, require large lump-sum capital expenditure, and have a long project life. Also, their commodity products are usually undifferentiated and a taker of a single price in the market at any point in time due to the global exchange trading of many mineral commodities (Luis A Martinez & McKibben, 2010; Topal, 2008). Because of these characteristics, which increase the strategic importance of new mine investment decisions in the mining business, mining firms have a great need for appropriate project valuation techniques.

2.2 How to Select New Investments – Discounted Cash Flow Analysis

2.2.1 Theory of Project Valuation and Selection

When a mining company faces different investment opportunities, it is necessary to evaluate the different projects for their attractiveness, based on two principles: 1) bigger benefits are preferable to smaller benefits; 2) early benefits are preferable to later benefits (O’Neil & Gentry, 1992). Although the benefits could include strategic considerations, they predominantly refer to the tangible benefit of cash flow, which is calculated as the cash benefits of a project minus the cash costs of the projects.
Based on classic corporate finance, the widely accepted tool in evaluating capital investment projects in mining and other industries is the Discounted Cash Flow (DCF) method (Guzman, 1991; Luis A Martinez & McKibben, 2010; O'Neil & Gentry, 1992). The DCF method requires the determination of periodic project cash flows over a uniform planning period and consideration of the time value of money by using an appropriate discount rate (O'Neil & Gentry, 1992).

The present value of cash flows in the different periods is calculated by discounting them to the present time with the specified discount rate. To evaluate a project, the present values of all the positive and negative cash flows are then summed to calculate the net present value, which is the well-accepted theoretically correct evaluation criterion for financial and industrial projects (Brealey et al., 1992; Bussey, 1978; Hirschleifer, 1958).

The NPV for a typical mining project is calculated as the sum of time-discounted expected net cash flow from all the periods within the planning horizon, minus the capital investment, assuming that all the capital investment is made at the present (Luis A Martinez & McKibben, 2010). If the NPV is positive, the project is generally undertaken because the financial benefits exceed the costs under the given discount rate. Otherwise, the project is generally not chosen.

\[
NPV = \sum_{t=1}^{T} \text{present value of cash benefits} - \sum_{t=1}^{T} \text{present value of cash costs}
\]

\[
= \sum_{t=1}^{T} \frac{E \{CF_t\}}{(1 + R)^t} - \text{capital investment}
\]

\[
CF_t = \text{production quantity} \times \text{grade}_t \times \text{recovery rate} \times \text{price}_t - \text{production costs}_t
\]

T is the planning period over which we are evaluating the different proposals.

As can be seen in the equation above, price has a significant impact on the NPV because it is often a highly volatile factor, unlike the other components of cash flow which are more predictable and stable. Furthermore, the expected cash flow, \( E \{CF_t\} \), is not equivalent to the cash flow at the expected price, because the production quantity (and by extension the
production costs) is linked to price since firms will produce up to their marginal cost of production in order to maximize profit.

R, the discount rate used, also has a significant impact on the NPV. The discount rate is typically calculated using the weighted average cost of capital for the firm and aims to represent all sources of uncertainty in the project, including technical, geopolitical, legal, financing, commodity price and other market concerns, as well as the time value of money (Luis A Martinez & McKibben, 2010). It could also be interpreted as the internal hurdle rate that the company requires for making an investment, which would also include consideration of project risks (Cavender, 1998). Positive NPV for a proposed project indicates that the project will yield a return in excess of the hurdle rate used in the method and hence should be accepted.

2.2.2 The Related Method of Internal Rate of Return and Its Deficiencies

Another DCF technique, the internal rate of return (IRR), has been widely used in the mining industry as the project-evaluation criterion and has been defended as an evaluation method suitable as the NPV analysis (Hajdasinski, 2000; O’Neil & Gentry, 1992). The IRR is defined as the interest rate that equates the sum of the present value of cash benefits with the sum of the present value of cash costs for a project, i.e. the discount rate that results in a zero NPV (O’Neil & Gentry, 1992). If the IRR calculated meets or exceeds the required rate of return of the firm, then the project is typically accepted. Potential project choices could be ranked by their IRR, much as they could be ranked by the NPV.

Although on the surface, project evaluation using the IRR seems equivalent to evaluation using the NPV. However, the two are not always compatible for two reasons. First, there might be more than one IRR that one can calculate for a project, whereas there is only one NPV. The IRR is only guaranteed to be unique if the project only has one sign-change in its cash flow (i.e. all capital expenditure that exceeds the net cash benefits from the period is spent in one period).

Second, even when the IRR is unique, the NPV method and the IRR method might not produce the same desirability ranking for two mutually-exclusive projects (please see an example on page 458 of O’Neil & Gentry (1992)). The difference in ranking is the result of different implied assumptions for reinvestment rates for the funds generated by a project under the two methods.
As O’Neil & Gentry (1992) explains, the IRR represents the rate of interest earned on the unrecovered part of the investment such that the remaining periods’ cash flows make the unrecovered portion equal to zero at the end of the period used for evaluation. This means that for the entire investment expenditure to earn the IRR, the intermediate cash flows must be reinvested at the IRR for the remaining period of evaluation.

The NPV method, on the other hand, assumes reinvestment of the cash flow at a rate equal to the specified discount rate (i.e. the required hurdle rate). The NPV method is more theoretically sound for not assuming that the reinvestment interest rate for one proposed project would be different from that of another project of the same firm, since there is nothing to justify such difference. Hence, despite being similarly rooted in the DCF analysis, the NPV method is preferred over the IRR method for ranking potential projects and will be the basis of the different methodologies in this thesis, and it will be referred to interchangeably as DCF analysis (Hajdasinski, 2000; O’Neil & Gentry, 1992).

2.3 Problems and Issues in Using Static Discounted Cash Flow Analysis

2.3.1 Conceptual and Practical problems in applying the DCF analysis

The concept of DCF and NPV is theoretically sound. However, in practice, the determination of the cash flow is challenging, because we have limited ability to control or predict future market conditions which affect the price and cash flow. The most significant mining project uncertainties and risks are in mineral reserve size, ore grade, mineral price, operating cost, capital cost, sociopolitical instabilities and mine management (Smith, 2002; Topal, 2008). Uncertainty in commodity prices is often the most important source of uncertainty in mining project investment evaluation, especially in recent years when commodity price volatility has been especially high (Auger & Guzmán, 2010).

The standard DCF approach for evaluating mining projects is the static DCF method, where a project is completely described by a static stream of expected cash flows (Chevalier-Roignant, Flath, Huchzermeier, & Trigeorgis, 2011). The static DCF method is based on expected or median value of uncertain variables and does not account adequately or correctly for randomness in these variables (L A Martinez, 2009; Samis, Martinez, Davis, & Whyte, 2011). The usual
practice of calculating NPV based on *expected prices* produces NPVs that could be substantially different from the *expected NPV* based on different potential prices. This is because NPV is not linear in price (see the formula for cash flow and discussion of why expected cash flow is not equivalent to cash flow at the expected price on page 17), making it important to incorporate the uncertainty at the factor level rather than the NPV level (Auger & Guzman, 2010).

Besides not accounting adequately for randomness in cash flow variables, a second flaw of the static DCF analysis is that it implicitly assumes that the proposed project is a now-or-never proposition when evaluating irreversible projects such as new mines, and does not account for flexibility in operations in response to changes in market conditions (Dixit & Pindyck, 1995). In the real world, the ability to delay investing in a project and to operate it flexibly (e.g. temporary halting of production) affects the decision to make the investment now. The option to defer the project until a more favorable time, as well as managerial flexibility in determining firm output, could affect the value of a project. However, DCF assumes that the investment is a now-or-never decision, ignores the option to delay the investment to some future time (Makropoulou, 2011), and does not account for managerial flexibility in responding to future uncertain conditions (Guzman, 1991; Luis A Martinez & McKibben, 2010).

Third, static DCF analysis is traditionally applied at the mine project cash flow level to evaluate whether it would be a profitable venture and which proposed mine to choose (Cavender, 1998; O’Neil & Gentry, 1992). The proposed mine is treated in isolation from the rest of the firm. However, it might be necessary to consider the impact of opening the new mine on the profitability of the rest of the company’s portfolio in at least the same mineral, because new volume could lower the market price of the commodity, hurting profit for the firms’ other mines. The potential negative price and profit impact are especially significant when the mine in question is substantial in size compared to the market supply, and when the firm has a large volume of existing mines that would be affected by the price impact (Murto, Näsäkkälä, & Keppo, 2004). Oligopolistic markets tend to have these characteristics and a firm-level DCF analysis on new mine opening decisions could provide much more sound investment decision-making than looking at the cash flow of potential new mines alone.
For oligopolistic markets, a fourth flaw of the static DCF analysis is that a firm’s mine opening decisions might not only affect the profitability of its other mines, but also the profitability of the other firms in the market. Because firms’ decisions affect one another’s profit and, hence, potential future decisions, it might be beneficial for firms to engage in strategic behavior, such as opening certain negative-NPV mines in order to pre-empt others from opening, thereby obtaining a better overall cash flow in the long run. In the game theory literature, this type of market is well-recognized and the competitive decision-making within it is known as a Stackelberg or Cournot competition, depending on whether the firms make decisions sequentially or simultaneously (Fudenberg & Tirole, 1993). Not incorporating such game strategic consideration might result in suboptimal capital investment decisions by the firms in an oligopolistic market.

2.3.2 More Sophisticated NPV Approaches to Mitigate the Problems

Conscious of the complexities discussed above that render conventional static DCF analysis inadequate, industries and researchers have created more sophisticated approaches to conducting capital investment project evaluation. This section discusses the main methodological advances in literature that mitigate the methodological mining market-specific concerns mentioned in the last section.

**Dealing with Uncertainties**

As discussed, the static NPV method does not address adequately or correctly the uncertainties in the cash flow due to market and other future conditions. Several approaches have been developed to incorporate considerations for uncertainty into the analysis.

Regardless of the project evaluation technique used, the NPV value that correctly accounts for uncertainty is the expected NPV over the space of potential values for the uncertain parameters, instead of the NPV based on expected values for the uncertain parameters. As discussed in the previous section, the two are not equivalent (Auger & Guzmán, 2010).

Besides aggregating the different uncertainties into a single expected NPV number, examining the likelihood of potential NPV separately also provides useful information for investment decision-making. A common method used in the mining industry is sensitivity analysis, where the values of uncertain factors are varied — usually one at a time — to gauge their impact on
profitability (Celebi & Pasamehmetoglu, 1990). This approach is straightforward, but it cannot quantify the probability of an investment outcome.

A more advanced technique that could measure uncertainty and generate a probability profile of potential outcomes is the Monte Carlo simulation technique, where probabilities for different uncertain events are specified and the space of possible scenarios are sampled randomly through simulation. The Monte Carlo simulation is widely used for risk analysis in evaluating prospective mines (Celebi & Pasamehmetoglu, 1990). The two main drawbacks of the Monte Carlo analysis are the subjective assignment of probabilities to the uncertain factors and the computational intensity of conducting a large number of simulations to generate statistically significant results.

When some information is available about future economic circumstances, but not exact probabilities, Celebi and Pasamehmetoglu (1990) propose an approach that combines qualitative and quantitative information on risks. It is based on an a priori ranking of the likelihood of future conditions, which then can be used to determine the maximum and minimum expected payoff and also the maximum and minimum variance for the different mine options.

**Accounting for Ability to Delay and Operating Flexibilities – Real Options**

Academic research has recommended the use of real options in project economic evaluation to account for uncertainty and the value of flexibility and waiting (Dixit & Pindyck, 1994; Samis et al., 2011).

Robert Pindyck, who pioneered the field of real options for economic evaluation of projects, wrote a detailed treatise on why the traditional method of static DCF does not adequately capture the uncertainty and valuation contingent on uncertainty that exist in projects, nor the value of waiting and keeping the option to invest alive (Pindyck, 1986). This problem is especially severe in cases where the investment is not reversible. He shows that, when the investment is irreversible, as it is in starting a new mine, and future demand conditions are uncertain, making the decision to invest involves the exercising or giving up the option to wait for new information and then invest. The cash flow should properly include this lost option value as well as the actual investment cost (Pindyck, 1986).
Numerous studies illustrate how the traditional DCF could undervalue a project, a comprehensive summary table of which is provided in Shafiee, Topal, & Nehring (2009). Using real options valuation, firm decision-making can capture more of the investment opportunities that would be profitable when managerial discretion is accounted for. It can also lead to better timing decisions on investing versus delaying on a project that currently has a positive valuation. The operating flexibilities that real options seek to capture are realistic and present -- Moel & Tufano (2002) found in an empirical study of North American gold mines that the real options model is realistic for accounting for mines’ opening and closing decisions in response to gold price changes.

The incorporation of real options analysis into the DCF analysis could be informal and qualitative (e.g. Slater, Reddy, & Zwirlein, 1998). It could also be more formally built into the model through several different ways of implementation, including partial differential equations, Monte Carlo simulation, decision tree analysis, etc, as discussed in Section 3.3.2.

Besides Pindyck’s seminal work, several papers also demonstrate the usefulness of real options in mining project evaluation. Brennan & Schwartz (1985) first used the principles of real options to not only evaluate a copper mine but also assess the optimal timing of opening through a stochastic optimal control model implementation of real options. The model assumes a stochastic price process and operating flexibility in opening, temporarily closing, or abandoning a mine. Lin (2004) also uses a dynamic option simulation approach to evaluate natural resource investment, but uses a finite reserve with additional options to accelerate the mining speed. Haque, Topal, & Lilford (2014) employs and improves upon a partial differential equations implementation to show how to implement real options analysis numerically on a hypothetical gold mine.

**Expanding the Scope of Cash Flow Considered**

Cavender (1998) observes that traditional capital budgeting considers the profitability of individual projects, but not their impact on overall strategy, which could affect their core competitiveness and, hence, long term profitability. An important aspect of a firm’s strategy is the long term profitability of its portfolio, instead of just the prospective mine that it is considering to open. In an oligopolistic market dominated by a few large players, the opening of
substantial new volume of production by one firm could negatively affect the price and, hence, the profitability of its existing mines. Therefore, even if the mine itself has a positive NPV, the impact on the firm’s overall profit could be negative. The focus of the traditional mine investment NPV analysis on individual projects, and the lack of consideration for its impact on price and the profitability at the firm level, has received much attention from investment analysts in the iron ore industry (Gait et al., 2013; Knights, 2013; Toyne, 2013). However, evaluation of mine investments in the literature cited in this chapter continues to be based on the cash flow of the prospective projects themselves. The exceptions where firms try to optimize NPV on the firm level instead of mine level are only found in the game theory literature discussed in the next section.

**Strategic Game-Playing in Oligopolistic Markets**

As discussed in the section on real options, there is value to delaying opening; sometimes, waiting to open is optimal (Brennan & Schwartz, 1985; Majd & Pindyck, 1987; Pindyck, 1986). In oligopolistic markets with a few large firms, not only do the firms’ decisions to open and their timing affect their own profit, but also that of other firms through impacts on the market price. Due to the threat of potential opening from other firms, the optimal timing of opening could change (Joaquin & Khanna, 2001). The evaluation of mining investment decisions that incorporate firms’ strategic interactions in such markets of imperfect competition and the firms’ options to delay and operate flexibly are referred to as real option games, because they incorporate real options and game theory principles (Chevalier-Roignant et al., 2011). In real option games, firms condition their decision not only on exogenous variables, but also on the actions and potential reactions of their competitors, with the cash flows as their payoffs (Chevalier-Roignant et al., 2011).

Real option games allow the examination of the trade-off between the opportunity cost of committing the capital expenditure and the expected future strategic benefits from it (Chevalier-Roignant et al., 2011). Early overinvestment might be optimal when the early-committing firm’s actions result in negative externality for its competitors and deter others from entering the market, and the inverse is true as well. Uncertainty in future conditions might lessen the incentive to make a sunken capital investment.
There is a large volume of literature on the topic of real option games since they were first proposed in the 1990s, mainly differing from one another along the dimensions of the payoff structure, continuous versus discrete time, incremental versus lumpy investment, exogenous competition vs endogenous competition, the number of players in the market, the completeness of information, type of demand shock, and simultaneous vs. leader/follower investments. Chevalier-Roignant et al., (2011) contains an extensive review of the literature in this space, including a table summarizing the contribution of all the major articles, which we will not repeat here.

For practical mining applications, the real option games have lumpy investment (i.e., not usually possible to develop only part of the mine), discrete time, and the payoff for each firm is basically dependent on the volume of production operating, its operating cost, and the price in the market. Most papers use a highly theoretical approach and examine the analytical solutions to the real option game of very stylized markets. The markets are predominantly either duopoly/oligopoly with homogenous firms or a non-symmetric duopoly (e.g. Dixit & Pindyck, 1994; Joaquin & Khanna, 2001). Only two studies use a numerical simulation and analysis approach, which is more pragmatic for firms to implement, to examine the dynamics of the real options games, but even then with highly stylized markets and firms defined entirely by smooth analytical functions and homogeneous firms (Aguerrevere, 2003; Murto et al., 2004). Unlike the literature for incorporating uncertainty correctly into the DCF analysis and for real options, the author is not aware of any study that explores how an oligopolistic market and firms with realistic features (e.g. non-smooth supply curve, heterogeneity among firms) might function in a real option game setting.

2.4 Practical Obstacles towards Implementation of Advances in DCF Analysis

2.4.1 How Real Firms Conduct Investment Planning

Despite all advanced methods available that integrate more of the uncertainties and complexities of the real world, Mirakovski, Krstev, Krstev, & Petrovski (2010) estimates that 75% of the mining firms use the traditional DCF method in new project evaluation, because of the complexity in applying the decision tree and Monte Carlo method, especially as the number of uncertain variables increases. Their estimation agrees with a survey of twenty mining companies
conducted in the early 1990s, where the internal rate of returns (IRR) and the net present value (NPV), two incarnations of the static DCF method, were found to be the dominant choice for mining investment evaluation and capital budget decision making, with 95% of the surveyed companies reporting using one or both as a primary metric (Bhappu & Guzman, 1995). Payback period is a popular secondary tool. Only two out of the twenty companies also report using maximizing shareholding value or earnings per share as the primary criterion for making investments, which would consider the investment from a whole-firm-profit rather than a mine-project-profit perspective. Also, only two companies used more sophisticated techniques to capture the impact of uncertainty: options pricing in valuing copper properties, and Monte Carlo simulation for risk analysis on investment activities.

Although real option valuation is appealing from a theoretical perspective and has been widely recommended by the academic world, it is rarely used in the mining industry due to the mathematical complexity of the techniques (Brandão, Dyer, & Hahn, 2005; Cavender, 1998). Traditional and simpler DCF decision analysis is said to provide a more intuitive and viable alternative to real option, even though they might not always lead to the optimal decision (Brandão et al., 2005; Makropoulou, 2011; Copeland and Antikarov, 2001).

In terms of game theory methods, industry analysts have begun to realize that they are an important consideration, but only apply them in a qualitative, ad-hoc way (e.g. Toyne, 2013). The stringent assumptions of games, including perfect knowledge of the each other’s decision-making process, are difficult to meet in real life. Also, deriving the solutions to the real options game necessitates complex numerical methods such as dynamic programming, which also are difficult for mining firms to adopt.

In the world beyond mining industries, the adoption of more sophisticated capital budgeting tools (investment planning is a major part of capital budgeting) that incorporate real options reasoning and game theory principles is also spotty but more frequent in some industries than others. In an empirical study of the determinants of whether firms use more sophisticated tools among 189 large Dutch organizations, Verbeeten (2006) discovers that firms in the financial services industries and, to a lesser extent, the building construction and utilities industries use the more sophisticated methods far more than mining and manufacturing industries. An increase in firm
size or financial uncertainty (such as the uncertainty of commodity price for mining industries) is associated with higher use and importance of the more sophisticated investment planning methods.

2.4.2 Are the More Sophisticated Investment Decision Paradigms Helpful?

Although numerous research papers presented different improved theoretical models for evaluating mining investment decisions and sometimes illustrated them with numerical examples, as discussed in the previous sections, there are very few comparative studies of how well the different investment decision methods perform vis-a-vis one another, especially in realistic settings. The only three papers that the author is aware of are Moyen, Slade, & Uppal (1996), Topal (2008) and Auger & Guzmán (2010).

Moyen, Slade, & Uppal (1996) compare the value of mines when using the traditional DCF valuation method versus the real options valuation method under different market conditions. The mines are modeled based on data from recently opened Canadian copper mines and the evaluation is conducted by simulating the market with stochastic price and cost uncertainties. The real options method is implemented as a dynamic programming problem. The authors found that option value (i.e. value of operational flexibility and delay in opening) can increase the valuation of a potential mine by 0% to 100%, depending on the market parameters.

Dimitrakopoulos and Sabour (2007) test the usefulness and advantages of the real options valuation method and the static NPV method using simulations with multiple uncertainties. They apply the evaluation of the two methods to the question of which mine design to use for a hypothetical gold mine. Their results show that a different design is chosen when the real options valuation method is used, and that the real-options-valuation-based design generate 11-18% higher NPV than the alternative mine design.

Topal (2008) implements and compares three approaches to the evaluation of a fictional gold mine project – the static DCF method, decision tree analysis, Monte Carlo simulation, and real options. In the case study, despite producing different values, all the methods recommended accepting the project unless the hurdle rate reaches 36%, at which time only the real options valuation method still recommends the project. Despite the similarity in decision
recommendation, the author still recommends the real options valuation method, arguing that it more fully captures the value of operational flexibility in the face of uncertainty.

Although the three comparative studies show that real options as an investment method might generate large NPV payoffs for firms, they do not consider the project in the context of the rest of the firm, which might be impacted, nor do they account for their competitors’ decisions, which are important in an oligopolistic market. In an oligopoly, would more sophisticated investment decision methods still be superior? Would the integration of game theoretic thinking generate better NPV? And under what conditions? These are the questions we seek to explore in this thesis.

2.5 Thesis Question and Contribution: Comparing Models of Increasing Scope and Complexity

In the literature discussed above, different improvements have been suggested for the static NPV to capture more of the important dynamics in evaluating mining investment decisions. They comprise incorporating uncertainty correctly, considering the impact on the overall firm, including the value of delaying and operating flexibly, and modeling the strategic interactions in oligopolistic markets through real option games.

The more sophisticated models are challenging to use in industry due to their complexity of implementation; hence the majority of mining firms still utilize the traditional and static DCF analysis. A few comparisons between the real options method and the static NPV method show that the former produces superior realized NPV in simulated market settings. However, there is no comparison of the performance of investment evaluation methodologies when the market is oligopolistic, with major firms having significant influence on the market price and where a total-firm NPV evaluation approach or game-theoretic strategies might be advantageous. Do the more sophisticated investment decision methods deliver a NPV advantage?

This thesis seeks to take steps towards answering this question and filling the gap in literature. First, we specify the exact decision methods that this project is comparing. There are three investment decision methods (a.k.a. paradigms), in increasing complexity and scope of consideration, that this project seeks to examine and compare. Additionally, to examine the
potential for collusion in the market under different scenarios, a fourth investment paradigm is constructed to examine what happens when firms are allowed to collude – i.e. the joint-maximizing decision of the major firms.

The base investment decision method is the traditional DCF approach, which we term “positive-mine-NPV paradigm”. At any point in time, each firm examines its potential new mines and opens the one with the largest non-negative expected mine NPV, if any. This approach conforms with the static DCF’s assumption that the mining decision is a now-or-never decision at any point in time.

The second investment decision method is called “positive-firm-NPV paradigm”. In this decision method, the scope of cash flow considered in the NPV calculation is at the firm level in order to address the potential impact of a new mine on market price and thereby the profitability of the rest of the firm. At any point in time, each firm examines its potential new mines and opens the one with the largest non-negative expected firm NPV.

The third investment method is called “best-firm-NPV paradigm”. This decision method incorporates the real options consideration for the value of delaying mine opening and seeks to find the optimal time for opening for each mine instead of relying on positive NPV as the opening criteria. In addition, the firms under this method are assumed to behave in a game strategic manner because of the oligopoly setting.

The fourth investment method, the “cartel paradigm”, is unlike any of the previous three in that it assumes firms can and will collude on their opening decisions. Like the best-firm-NPV paradigm, this decision method also incorporates real options and optimizes the timing for each mine’s opening. However, it optimizes the joint NPV of the major firms instead of each firm individually. This decision paradigm is used to evaluate the NPV advantage of cartel decision making, which could potentially inform on the attractiveness of collusion under different market conditions. This is a secondary goal of the thesis.

The main three investment decision paradigms are summarized in Figure 1 below and the details of all four paradigms can be found in the appendix.
Figure 1: Investment Decision Paradigms Examined

Although we are trying to compare more basic methods against more sophisticated ones, there are some improvements upon the static DCF method that are so fundamental and relatively easy to implement numerically that we have included them for all the different investment decision methods. First, the expected NPV we are using is always the expected NPV over the different demand scenarios, not the NPV given the expected demand. Second, operational flexibility is assumed for all the methods. If the price becomes unprofitable for a mine to produce, the mine could temporarily close. Even though operational flexibility is usually only included in real options analysis, in real life, a firm’s ability to close a mine does not depend on which investment decision paradigm it chooses. Hence, to allow fair comparison of the different decision methods, we have assumed operational flexibility for the firms regardless of which investment decision method is used.

The market setting we will focus on in this thesis is 3-firm oligopoly with many smaller firms in the rest of the world (ROW), because 2-player has been solved analytically in previous literature, and because 3-player is more realistic for the many markets where antitrust laws often prevent the market from being a duopoly. The single source of exogenous stochastic uncertainty is the market demand, since price is modeled endogenously as determined by supply and demand.
Chapter 3 – Methodology

This chapter introduces the market and decision models that have been developed to explore the impact of adopting different investment decision paradigms on the market-level and firm-level outcomes.

3.1 Overall Structure and Approach in Comparing Different Mining Investment Decision Paradigms

3.1.1 Methodology Structure and Process Flow

To evaluate the impact of different mining investment decision methods on the firm and market outcomes, this thesis builds several models and computational modules, outlined in the diagram below and described in detail in the subsequent sections.

First, each decision paradigm is modeled mathematically into a set of rules for the opening of new mines. The resulting decision models for the positive-mine-NPV paradigm and the positive-firm-NPV paradigm are applied directly in market simulation because no optimization is needed for the paradigm of opening up mines based on whether NPV is positive. The best-firm-NPV paradigm and the cartel paradigm, on the other hand, need to run through an optimization module to generate the strategy of new mine openings that would generate the optimal expected cash flow NPV for the firm or the mine over the 27 years. To examine how the different strategies that generate the optimal expected cash flow NPV under each decision paradigm would perform in the real world where there is uncertainty, we run a Monte Carlo simulation of the market over 27 years with stochastic demand perturbation. The firm and market outputs from the simulation (i.e. price, quantity and cash flow from the simulation for each firm and the overall market) are the metrics by which we evaluate the relative quality of decision paradigms. Both the decision optimization module and the market Monte Carlo simulation module rely on the market supply-demand model for market clearance and price determination given the supply and demand in any period. The supply and demand parameters into the market model could be varied to generate different market scenarios for testing, as the analysis chapter will discuss.
Figure 2: Overall Model Structure

All model components are implemented in Matlab, and the pseudocode for the key models and modules is contained in the appendix. The major design considerations of each of the main components are described in the sections that follow.

3.1.2 Model and Analysis Design Philosophy: Coherence and Correspondence

The research design is based on both the notion of coherence and correspondence (Hammond, 1996). The formulation of the models is rooted in the principles of microeconomics and abstracted from the real world to focus on the supply-demand dynamics. The analysis framework, however, is more numerical than theoretical, using a realistic fictional market with parameters that correspond closely to certain real-world mineral markets. This numerical analysis approach is adopted because theoretical analysis of the full dynamics of three-firm oligopoly under exogenous uncertainty is very difficult (Murto et al., 2004). Furthermore, the
combination of stylized supply-demand models and numerical analysis of a realistic case study increases the accessibility and relevance of the analysis to the real world while keeping the focus on the core dynamics.

3.2 Market Supply-Demand Model

Unlike much of previous literature on real options, this thesis does not assume price as a separate variable with a defined stochastic transition. Because we are interested in oligopoly, where the major firms' dominant market position and large incentive mines enables their investment decisions to affect the market volume and, hence, price significantly, price is modeled endogenously, treated as dependent on supply and demand through a market supply-demand model. The market supply-demand model is central to both the decision-making process of the firms in forming their price expectations and the running of the market simulation in calculating the prices resulting from different decisions. The key dynamics of this model are discussed below.

3.2.1 Market Supply-Demand Model Framework and Market Clearing Principles

The market supply-demand model is essential to translating supply and demand into market price and quantity, both for the firm's forecasting purpose during its decision-making process and for finding out the impact of supply decisions and demand perturbations during the simulation. This thesis models an oligopolistic market with three major players for a homogenous non-storable commodity. Oligopoly, a structure of several commodity markets, is chosen to focus on examining the differences in decision-making and outcomes under game and non-game theory paradigms. The degree of market concentration will be varied in the analysis to examine the impact of market competitiveness on the value of different decision paradigms. The modeled commodity is non-storable, eliminating the need to model inventory dynamics in the market model, which would vastly increase the analysis runtime. Non-storability is a realistic and relevant assumption because, as the SME Mining Engineering Handbook (Darling, 2011) mentions, many mineral products "are not amenable to large-scale stockpiling" due to high storage-cost-to-value ratio, among other factors.

The market clearing mechanism of the market model is rooted in microeconomic theory, which says that, in the short-run, competitive firms will have an incentive to produce as long as price
covers average variable costs (which is termed "opex"\textsuperscript{1} in this thesis for concision) (Tilton, 1992). The market model also assumes that recurring costs are predominantly variable, and opex per unit is stable regardless of whether the mine is producing at 1% or 99% utilization rate of its capacity. Hence, the opex for a mine is the same for all capacity utilization levels and mines can stop producing without incurring an ongoing charge when the price falls below their opex.

Also, the supply-demand model assumes that the market clears in the same period completely (i.e. supply that is produced in a period = realized demand in the period). Hence, the price in this market will always reflect the opex of the marginal producer. This market is termed a "competitive market" in terms of its supply situation (even if it has an oligopolistic structure), where the firms are takers of the price resulting from the supply and demand situation, vis-a-vis "producer market", where the producer can set their own price which is independent of the marginal cost (Tilton, 1992).

The mathematical mechanism used in the market model for this thesis is adopted from a previous paper on a similar topic of inquiry (Murto et al., 2004). Following the paper’s method, market demand is parameterized as a constant-price-elasticity demand function (please see the appendix for demand function details), and price clears at the intersection of the demand curve and the market supply curve, which is a traditional “stair-step” curve commonly used to model market aggregate supply curve for commodities (Poulizac, 2013). All mines with operating cost at or below the intersection point operate in the market, whereas the mines above the intersection point are not producing in the period without any temporary shutdown cost.

If the marginal mine is not fully utilized at the crossing point, the unutilized capacity is shared proportionally by all mines that are operating, as would happen in the real world if firms have equal access to the marketplace and downstream customers. The utilization rate, however, does not impact the operating mine’s operating costs – for simplicity the market model assumes that the marginal operating per unit does not change as long as the mine is producing at all. This

\textsuperscript{1} Opex includes sustaining capex (ongoing capital expenditure needed to sustain the same level of production, as discussed in Darling (2011)}
assumption is commonly used in aggregate supply and demand modeling of commodity market, where the supply curve is in the shape of “stair-steps” (Tilton, 1992). If the demand curve crosses the supply curve between two mines, it is assumed that only the mines to the left of the intersection would operate (at 100% capacity in this case), because the mines to the right have higher operating costs and would not produce, and the price is still determined by the intersection of the supply and aggregate demand curve (though it would now be higher than the operating cost of the marginal mine).

3.2.2 Aggregate Supply Curve and Incentive Mines for the Major Firms

The aggregate supply curve used in this model is adapted from a real mineral market for realism and relevance of the decision models and simulations. The demand curve is stylized to examine the impact of growth pattern and stochasticity.

In this model, each major mine also owns up to three “incentive mines,” which are the mines that are ready to open if the market conditions meet the criteria of the decision-maker (according to the investment paradigm used). When the incentive mines are incentivized to open, they open without delay. Incentive mines are lumpy investment and each is either open or not open, without the possibility of a partial opening with reduced capex.

The aggregate supply curve (including existing and incentive mines color-coded by owner) is presented in Figure 3.
Figure 3: Total Supply Curve (Base Scenario). Inc-A, Inc-B, and Inc-C are the incentive mines of the firms respectively.
3.2.3 New Mine Additions by the Rest of the World

In addition to the incentive mines that belong to the major firms, the smaller mines in the rest of the world (ROW) also have mines that could open. These mines are typically not considered price makers because of the small volume of individual firms, nor are they considered firm-level strategic players, because each firm has few mines and hence firm-level strategy is similar to mine-level strategy. However, in bulk, these mines have a substantial impact on price and would influence the strategy of the major firms. Some major firms might decide to expand in order to preclude the market price from rising to a level where smaller firms enter, which would depress price. The price depression is especially significant when the new and smaller entrants are market price takers, and, in a quest to recuperate capital costs and because of liquidity constraints, these new entrants will produce at full capacity regardless of the demand and price in the market. In this case, the negative price impact of their entrance will last long after the price falls below their relatively high opex, essentially taking demand away from the major firms for as long as the entrants’ mines are not exhausted.

The price level that would incentivize the ROW mines to open based on only mine NPV consideration is typically higher than the price that would lead the major mines to open, because scale economics and bargaining power typically lead smaller firms to have more capex and opex per unit production than larger mines (Tilton, 1992).

To incorporate the ROW expansion into my model dynamic, the salient traits of the ROW new entrants discussed above are emphasized and the firms are modeled as anonymous ROW firms with extremely low effective opex (so that they will produce regardless of the demand and price in the market). Their actual opex does not matter, because the model only looks at the profit outcome for the major firms, not the minor ones. Also, placing these ROW new entrants at the very low end of the supply curve emphasizes the sustained depressing effect they have on the market price and the sustained displacement of demand from existing possibly major firms (i.e. effectively shifting the entire supply curve to the right). Also, this ensures that the new entrants are always price takers, and not makers, because they will never be the marginal mine.
To incorporate the ROW expansion into the dynamic programming model, the new ROW supply needed to be discretized to a few incentive price levels to allow the model to run in a reasonable time frame. Three bundles of new ROW supply would come on at the 60th, 70th, and 80th percentile price of the existing supply curve, each accounting for around 3% of the existing total world supply, or equivalent to the size of an average incentive mine of a major firm. Together, the ROW incentive mine account for 9% of the existing market volume, or about the same impact as a major firm that decides to open all three mines. The incentive price levels for the ROW mines were set to start at just above the zero-mine-NPV price level of the major firms to reflect the higher capex and opex of the minor firms, as discussed above.

3.2.4 Assumptions on Mine Opening and Closing Dynamics

One important managerial flexibility is the ability to open and close existing mines as market conditions change. In an empirical study of 285 North American gold mines’ opening and closing decisions, Moel & Tufano (2002) note that this flexibility is used frequently. They also found that the decisions are affected by the price and volatility of gold, operating cost, proxies for closing costs and size of the reserves.

In this thesis, the market model captures this important flexibility and drives the decision to close/open an existing mine by two of the four factors mentioned: the operating cost of the mines and the price of the mineral (determined by supply, underlying demand, and demand perturbation). Existing mines can temporarily halt production immediately once the commodity price falls below the level of its opex. Closing costs are assumed to be zero for simplicity of modeling and maximization of the flexibility feature. No transition cost or ramping time is assumed for the operation to halt or to restart, and the mine is assumed to be able to produce at its previous level upon re-opening.

According to literature, temporary mine closing are difficult to execute in practice (Shafiee et al., 2009) or would entail substantial cost (Moel & Tufano, 2002). Also, when faced with lower prices, mines with high fixed costs might expand instead of reduce production to lower their unit operating costs, a dynamic that is contrary to the one present in the thesis market model (Humphreys, 1996). The high operating flexibility is most appropriate for the industrial minerals sector and alluvial operations (e.g. gold, tin) with lower fixed costs (Humphreys, 1996). In future
work and when applying the models in this thesis to specific minerals, the cost and ramping time of closing and re-opening could be incorporated into the model to capture these sector-specific dynamics of mine supply change.

3.2.5 Demand Evolution

The model used in this thesis assumes an underlying demand level for each period. As discussed in the market clearing section, the actual realized demand in each period is a function of the supply curve and the downward sloping demand curve with fixed elasticity. This "underlying demand level" specifies what the demand level in that period would be at the "period 0 price", i.e. the price in the first period without any new mine opening. The underlying demand level in all periods is known by all the firms in period 0.

Although the underlying demand is specified, during the market simulation, there is still some demand uncertainty from two sources:

1) unexpected perturbation to demand, of a fixed magnitude and probability, that actualizes every period after all the firms already made their mine opening decisions (In the base case this is a 5% perturbation from the base with a symmetrical 10% probability of positive/negative shock);

2) permanent demand up- and down-shifts that happen as a result of the market price reaching certain levels, which trigger additional reversible substitution into and from the mineral from other markets.

Although this mostly deterministic demand path is different from the models in the real options valuation literature, where demand is assumed to evolve stochastically with a certain level of volatility (Haque et al., 2014; Murto et al., 2004), it is nevertheless a relevant model of the market reality. In the real world, firms could be assumed to have a reasonable level of information on the underlying drivers of mineral demand because of the various sources of underlying demand projections available (e.g. USGS and other government agencies, CRU, Wood Mackenzie, etc), if no significant shocks happen due to exogenous forces such as technology breakthrough on new material substitutes, permanent geopolitical changes in mining regions, or dramatic macroeconomic events that affect demand. The main drivers of uncertainty
that could be anticipated are short-term shocks (due to supply chain disruption, etc), price-driven substitution from other minerals and materials, and price effects on the demand quantity. This model is no less realistic than the typical stochastic demand process used by previous models, which had an increasing range of possible demand in the farther future periods but no outlook on what demand path is more likely. The key difference is that this thesis assumes that the firms have reasonably accurate expectation of how future baseline demand will evolve. Practically, the modeling choice of a pre-determined demand path means that we could observe how the opening strategies of the firms would change if they expected the demand to evolve differently in the future.

3.3 Finding the Optimal Policy under Best-Firm-NPV and Cartel Decision Paradigm

As discussed, because the best-firm-NPV paradigm and the cartel decision paradigm both seek to make decisions for each period such that the overall NPV of the cash flow over all the years for either the firm or the cartel is maximized, these two paradigms cannot be applied directly in a market simulation, but rather need to be optimized to generate the optimal policies first.

In this thesis, we structure the two paradigms as decision trees and use dynamic programming to generate the optimal policies under the two paradigms. The optimal policy specifies for each period the optimal mine opening choice that gives the best expected cash flow NPV, given a supply and demand situation, the mines that have already been opened, and any permanent demand shift triggered by reaching certain price points.

3.3.1 Investment Decision Model and Firms’ Decision-Making Process

All four models of decision paradigms make decisions for 27 decision periods, the largest number of years possible while maintaining a feasible time for decision model optimization. Each decision period represents one year, and in any year, all three major firms make decisions in a specified sequence (which remains the same over time). The market clears at the end of each year and the rest of the world (i.e. smaller firms) reacts to the price by potentially entering then (see Section 3.2.3 for a description of why and how). Having the market clear after each round of all firms making decisions is in contrast to the models developed in previous literature for
oligopoly settings, where the firms make decision in fixed sequence but the market clears at the end of each firm’s decision (Azevedo & Paxson, 2011; Dixit & Pindyck, 1994). This is a conscious design decision in order to minimize the temporary monopolistic advantage enjoyed by the decision leader in the previous models. In the real world, there is no reason why multiple firms cannot each decide to open a mine within the same year in response to another firm’s decision, making any temporary monopoly advantage due to being the first to make a decision much more transient than a year.

3.3.2 Modeling Real Options as Decision Tree Analysis

Decision tree analysis is a valid approach to implementing real options analysis. There are three main numerical techniques for project valuation using real options, based on classic evaluation techniques for financial options (Lin, 2004). First, various lattice and tree approaches such as Cox, Ross, & Rubinstein (1979) binomial tree method could be used to map out all the uncertainty-contingent valuations. Second, a partial differential equation could be discretized by Finite Difference methods such as in (Brennan & Schwartz, 1978). Finally, in cases where the state variable space is large, making the first two methods infeasible in terms of runtime, the underlying stochastic process could be approximated by Monte Carlo simulation and the option could be priced accordingly (Lin, 2004).

Out of these approaches, the binomial decision tree implementation provides a computationally intensive but more intuitive solution (Brandão, Dyer, & Hahn, 2005). Hence, this thesis uses the decision tree implementation, with dynamic programming to optimize the value of opening a mine at each time point, contingent on previous mine opening choices and current supply and demand conditions. The state space has been kept simplified for computational feasibility and to capture the salient features of the problem. The pseudocode in the appendix outlines how the decision tree method and the dynamic programming optimization are implemented in Matlab.

3.3.3 Modeling Game Theory Interactions in the Best-Firm-NPV Decision Paradigm

Under the best-firm-NPV investment decision paradigm, the firms individually seek to maximize their firm cash flow NPV without the possibility of collusion, while being aware of how other firms might act or react in response. This is a three-player game theoretic model, and the optimal and stable mine openings in such a situation would be the Markov-perfect Nash equilibrium for
this game, which is difficult to solve analytically because the game contains three firms and the price determination does not have a neat analytical form (Murto et al., 2004).

To solve for the Nash equilibrium optimal policy for the firms, the game could be implemented as either a sequential game (where the firms take turn in making mine opening decisions) or simultaneous game (where they make opening decisions at the same time). Following the implementation approach for a similar real options capacity game in Murto et al. (2004), we assume that firms make decisions sequentially and in a fixed order (we will vary this order to see its impact on the simulation outcomes in the analysis section). This ensures a unique Nash equilibrium solution. The game is then solved using backward induction (see appendix for pseudocode).

3.3.4 Interpretation of the discount rate

In traditional NPV analysis, the discount rate, often calculated using the weighted average cost of capital for the firm, aims to represent all sources of uncertainty in the project, including technical, geopolitical, legal, financing, commodity price and other market concerns (Luis A Martinez & McKibben, 2010). It could also be interpreted as the internal hurdle rate that the company requires for making an investment, which would also include consideration of project risks.

In the model and simulation in this thesis, we assume for simplicity that all the mines have the same risk profile and that the risk profile is stable over time. In practice, the use of a single global risk indicator is common because estimating an appropriate dynamic risk-adjusted rate of return is difficult (Luis A Martinez & McKibben, 2010).

In this thesis, the discount/return rate is set to be 8%, which is common for a number of large mining firms that the author has personal knowledge of. It is also varied in sensitivity analysis to study the impact of discount rate on decisions and optimal decision model.

3.4 Simulation Framework

In order to assess the relative performance of the four different decision paradigms in a realistic oligopolistic market setting, we run a Monte Carlo simulation of a fictional mineral market with
three major firms. The simulation is over a period of 27 years. The simulation and evaluation length of 27 years is chosen because it is the longest period with a feasible runtime for the computation of optimal best-firm-NPV and cartel policies in this thesis. Also, assuming the same cash flow per year, the discount year 28 cash flow would only be 1% of the total discounted cash flow in period 1 through 27, and can hence be safely excluded.

The stochastic element in the Monte Carlo simulation is a perturbation (+/- 10% to the underlying demand for the period) to the underlying demand level, which is uncorrelated across the years and has a fixed magnitude and probability corresponding to the parameters specified in the market supply-demand model.

For the analysis of most scenarios, the central case of no demand perturbation in any period is simulated along with nine other runs with stochastic perturbation for a total of 10 runs per scenario. Ideally, many more simulations should be run in order to estimate the probability distribution of the relative discounted cash flow resulting from following different investment paradigms. However, only 10 are run in this thesis to maintain a feasible computing time. 90 additional simulation runs with stochastic perturbation in demand are conducted for specifically analyzing the impact of perturbation magnitude and probability on the firms’ optimal decisions and cash flow NPV outcome.

### 3.5 Comparing the Decision Paradigms

The main goal of the thesis is to explore the firm and market behaviors that arise in an oligopolistic mineral commodity market when the firms use different types of investment decision paradigms, and which paradigms might offer better performance and under what conditions. The simulation described in the last section enables us to gauge the market and firm outcomes (market price, production quantity, cash flow etc.) under demand uncertainty when each of the decision paradigm is used. The “relative performance” of the paradigms should be measured by what matters the most to firms, which under classical microeconomics is profit or the NPV of profit for multi-year decisions. Hence, we compare the paradigms mainly by the metric of how the NPV of cash flows compare over the simulation period of 27 years. Other metrics such as price, quantity, and market share will also be examined when they are relevant.
3.6 Key Assumptions and Limitations of Methodology

The models used in this thesis are stylized in order to focus on important features and to reduce the runtime to a feasible level. Consequently, there are several important limitations to the model that would be interesting to improve upon numerically in future work when there is more computational resource.

3.6.1 Known Future Underlying Demand

In the investment decision models, mine opening decisions in any period are made based on the expected underlying demand for the current and future periods, which all the actors know with certainty. On top of the expected underlying demand is overlaid the stochastic demand perturbation, as well as potential permanent demand shifts as a result of reaching certain price trigger points for large-scale and persistent change into/out of this mineral by the demand side. The problem with this approach is that the demand level for each period is assumed to be very predictable and the degree of uncertainty is fixed and constant across time. In reality, the demand level farther into the future might be harder to predict than in the near future and could reach some extreme positions as a result of accumulated changes over time, which are not captured in the current model.

Instead of the having a fixed and pre-known underlying demand with a fixed-size, fixed-probability stochastic shock, we can model demand more realistically as a stochastic process where demand can either go up or down from the previous year, an approach that has been used in several papers in the past (Baldursson & Karatzas, 1997; Murto et al., 2004; Topal, 2008 (used to directly model price)).

Under the stochastic demand process, the uncertainty demand will be larger the farther we are looking into the future, capturing the uncertainty better. On the downside, modeling demand as a stochastic demand process would make it difficult to examine the impact of different patterns of correctly anticipated demand change (e.g. rising demand, falling demand, etc.) on the firms’ optimal mine opening policies and firm outcomes, which we are able to examine in the present model of fixed underlying demand path.
3.6.2 Assumption on Price-Formation Process

Price is formed based on the intersection of the supply and demand curves, which assumes either a market maker with full cost and demand information who is able to decide this price or an auction process with perfect information. This process is in contrast to the inventory-based pricing methods seen in system dynamics literature, because we are assuming a commodity with a high storage cost and hence no inter-temporal transferability.

In the real world, price is determined according to the trading structure of the market. The one that the market modeled in this thesis most resembles is metal exchange-based trading, where arbitrage and the large volume of trading means that any price difference between different markets are quickly traded away, and so there is practically only one global price for the mineral across the market at a point in time. In other markets, price could be heterogeneous and based on bilateral production contracts or be set by the producer if one dominates the market or if there is a physical shortage of supply (Tilton, 1992).

3.6.3 Type of Uncertainty Considered

Price uncertainty is a major source of uncertainty in mine evaluation; however, there are other significant uncertainties on the supply side as well, which we have not included in the model to keep the state space of the decision model optimization compact. According to the results of a Canadian Mineral Economics Society survey, the highest mining project risks come from mineral reserves and ore grade, political, social and environmental, metal price, profitability/operating cost, location, capital cost and management (Smith, 2002; Topal, 2008).

The additional supply-side uncertainties could be included in a more sophisticated market model to capture the dynamics of the interaction of the different uncertainties and how the optimal investment decision paradigm might change as a result. Previous papers provide guidance on incorporating these uncertainties (e.g. Slade, 2000, which models cost and reserve uncertainty in addition to price stochasticity in order to assess the empirical value of managerial flexibility based on twenty Canadian copper mines).
3.6.4 Impact of Inventory as a Market Feature

The market modeled in this thesis does not have inventory, which would expand the state space and runtime dramatically and make the current exact dynamic programming optimization method unworkable. The addition of inventory as a model feature could soften the impact of demand changes and reduce the payoff of opening new mines, as inventories are built up or reduced to meet demand changes. The assumption that inventory cannot be carried over from one year to another is applicable to many minerals which cannot be stockpiled in large quantities (Darling, 2011). For other minerals where inventory is a significant source of supply (e.g. copper), it would be important to incorporate inventory into the market model and adjust the optimization method from exact dynamic programming, which requires discrete state space, to approximate dynamic programming.

3.6.5 No Lag between Decision to Build and Production

In many mineral industries, it takes about 5-7 years to bring new supply on stream (Cuddington & Zellou, 2012). In the thesis, no construction lag is assumed, again to keep the state space compact and reduce runtime. Including a significant construction lag between deciding to open up new mines and having the new mines in production would result in more uncertainty in the payoff of a new mine and decrease the incentive to open. Also, if the firms do not have homogeneous construction lags, having lags could change the firms’ game strategies dramatically – i.e., even if a firm with a longer lag decides to open first, a firm with a shorter lag could react to it and still produce the extra volume ahead of the longer-lag firm’s opening and the resulting negative price impact.

3.6.6 Not Accounting for Expansion in Incentive Supply

This thesis assumes that all the new mines that could be opened in the next 27 years are already known at the present time. It does not take into account the discovery of new mines in the future, which might raise the incentive for firms to open now before more incentive mines from other firms become viable.
3.6.7 Price Hedging and Forward Sales Can Dampen Profit Loss Due to Opening New Volume

Mining company managers can sometimes also take advantage of price volatility and use hedging and forward sales programs to raise profitability in low price scenarios, a flexibility that is not accounted for in the current model (Bhappu & Guzman, 1995; Moyen et al., 1996). Perfect price hedging would eliminate completely the negative price impact from other firms’ new mine openings, rendering irrelevant the supply-price linkage which is central to the working of the current decision model.
Chapter 4 – Results and Analysis

4.1 Analysis Goals

The focus of the results and analysis section is how much better (or perhaps worse) the decisions based upon the more sophisticated optimization and game-theory based model are compared to those based on the simpler positive-firm-NPV and positive-mine-NPV based investment decision models. The quality of the investment decision model is evaluated primarily by the NPV of the cash flow generated over 27 years of Monte Carlo simulation of the market, supplemented by how turnover and market share change, which might also concern firms. Except for the examination of the effects of perturbation that need a higher number of runs to form useful conclusions, this thesis examine only the NPV outcome during the central case (i.e. the case) along with the maximum and minimum cash flow NPVs from 9 other random Monte Carlo runs due to time and computing power limitations. Future work could perform the analysis over a larger range of realized demand perturbations.

There are several parts to the results. First, we compare the market and firm outcomes from applying the optimal policy under the different investment decision-making paradigms in the base case scenario, which is constructed based on parameters from an actual minerals market with oligopoly characteristics. Next, we will examine how different market conditions and characteristics of supply and demand affect the relative performance (mainly measured by cash flow NPV) of the different policies for the different firms. Under the different demand and supply scenarios, we also explore how optimal capacity investment choices might change if the major firms are able to collude in investment decision making in a binding way. Finally, the impact of decision-making order on firms’ optimal decision and outcomes under the game-theory firm decision model will also be discussed and compared under a heterogeneous and a homogenous oligopoly.
4.2 Insights from the Base Case Scenario

4.2.1 Base Case Description

The base case of the model is set to represent a generic mineral market, with parameters that are realistic to specific markets. The discount rate used for the NPV analysis and decision optimization is set to 8%, demand perturbation magnitude factor to 0.95, demand perturbation probability to (0.1, 0.8, 0.1) for the negative/no/positive perturbation respectively, and the price elasticity of demand to 0.5 for inelastic demand. We assume a steady growth of 1% annually in the underlying demand (i.e. the market’s demand assuming that price does not change from the status quo).

4.2.2 Base Case Results Analysis

For the base case with 10 simulation runs of different realizations of demand perturbation, a comparison of the total firm cash flow NPV over the period of analysis (27 years) reveals results that conform to our intuition, as the chart of normalized NPV\(^2\) depicts in Figure 4 and the table of unnormalized NPV shows in Table 1. Key insights derived from the simulation are discussed in the sub-sections below.

Positive-mine-NPV policy: price collapse and over-expansion

The positive-mine-NPV policy, where a mine is opened based on whether its expected NPV for the next 27 years is positive and the most positive of all the potential mines of the same owner that could be opened, performs the worst when assessed from a firm NPV standpoint. This is because under the fairly favorable cost effectiveness of the incentive mines given the price resulting from the current level of supply and substantial demand, most of the mines quickly open in the early periods when assessed for the positivity of their NPV alone (see Figure 5), leading to depressed prices and but substantially more output quantity compared to the other

\(^2\) The NPV of the different policies for each firm is normalized to the level of the basic decision model of positive-mine-NPV to allow us to easily compare the relative magnitude and percentage difference between the basic decision model and more sophisticated ones.
decision policies, as can be seen in the price vs. output evolution graph in Figure 6. However, the increased quantity for the major three firms is not significant enough to offset the depression in price that lowers the profitability of the existing mines, resulting in overall lower firm cash flow NPV.

![NPV Comparison (normalized)](image)

**Figure 4: Comparison of Firm NPV under Different Investment Policies (Normalized so that the positive-mine-NPV policy's cash flow NPV is 100)**

3 Error ranges indicate the maximum and minimum of 10 Monte Carlo simulation runs. The bars represent the NPV when no perturbation occurs in the simulation. Note that the investment decision model takes the perturbation into account during decision optimization phase, even if a specific market simulation run does not experience demand perturbation.

4 Note that the No New Opening Policy is not a feasible policy in the sense that it does not derive from any objective-based investment rule of the firms, but rather simply dictates that no firm opens. Hence, even though the best NPV outcome for firm C and B occurs under this policy, it requires that firm A also does not open any mines, which is not a feasible market equilibrium because B and C not opening would keep the price higher and provide
Table 1: Unnormalized firm-level NPV of the firms under different decision paradigms

<table>
<thead>
<tr>
<th>Decision Paradigm</th>
<th>no opening</th>
<th>best-firm-NPV</th>
<th>positive-mine-NPV</th>
<th>positive-firm</th>
<th>cartel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm A</td>
<td>1.44</td>
<td>1.57</td>
<td>1.15</td>
<td>1.45</td>
<td>1.64</td>
</tr>
<tr>
<td>Firm B</td>
<td>1.08</td>
<td>0.98</td>
<td>0.72</td>
<td>0.92</td>
<td>1.01</td>
</tr>
<tr>
<td>Firm C</td>
<td>1.26</td>
<td>1.13</td>
<td>0.82</td>
<td>1.04</td>
<td>1.17</td>
</tr>
<tr>
<td>A+B+C</td>
<td>3.78</td>
<td>3.68</td>
<td>2.69</td>
<td>3.40</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Figure 5: Optimal mine opening decisions and production quantity under different policies

even more incentive for A to open. Although the No New Opening Policy cannot be realized in the market, it nevertheless provides a status quo reference for what the market would have been like if none of the firms were to open new mines and hence is included in the initial charts.

5 Dummy policy. See previous footnote.
Figure 6: Market price vs output quantity evolution under the different policies

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6 Using the results from the simulation run where no demand perturbation was realized. Henceforth, graphs without min/max intervals or any special note will use results from the simulation run with no demand perturbation, even though the decision model does incorporate consideration of demand perturbation.

7 The nodes and labels indicate the different time periods and the number 5, 10 and 15 overlap in some instances as the price-quantity path retraces over those of previous periods.
**Positive-firm-NPV policy: price sustained and output maximized**

The positive-firm-NPV decision policy differs from the positive-mine-NPV policy in that it considers not only the expected NPV of opening the project itself, but also the profit impact on the NPV of the existing mines of the firm and would only recommend the opening of a new mine if the overall expected NPV impact is positive. As expected, the firm NPV of such a policy outperforms that of the positive-mine-NPV policy significantly in the base case.

As we can see in the market price vs. output quantity graph (Figure 6), the price and quantity of the positive-mine-NPV and positive-firm-NPV policies converge in period 17 because, by that point, the mines that have been opened under either policy are the same. The positive firm-NPV policy simply leads to a change in the timing of the new mine openings, delaying them for firm advantage.

Do the policies with better overall cash flow NPV consistently deliver better cash flow in each period, or are they advantageous during some periods, but generate worse cash flow during others? As Figure 7 shows, the best-firm-NPV and positive-firm-NPV policy have better annual cash flow than the positive-mine-NPV policy in almost all periods (not that the cash flow includes the profits and capex annualized as a perpetuity from the year it is incurred). The undiscounted annual cash flow under the positive-mine-NPV policy converges, starting in period 17, with those under the positive-firm-NPV policies as the set of mines opened become identical and in the absence of a difference in either the permanent supply or demand shift. However, before the 17th period, both price and cash flow suffer from the undisciplined opening of the mines under the narrow-sighted policy of the positive-mine-NPV approach. In contrast, the slower opening pace under firm-opening policy expanded output while sustaining price.
Figure 7: Normalized undiscounted cash flow in different time periods, with capex annualized as a perpetuity (zero = cash flow of positive-mine-NPV policy)

Capex is annualized as a perpetuity from the moment they are opened in order to capture the difference in new mine investment among the different decision models. Perpetuity is a reasonable assumption because we assume mines have long operating lives in the model.
**Best-mine-NPV policy: game theory and inter-temporal optimization improves NPV outcome sometimes, raises price and reduces output**

From the perspective of maximizing the firms’ expected profit (a goal presumed of firms in classical microeconomics) and in the absence of binding collaboration in decision-making, the best-firm-NPV decision policy should be expected to perform the best, because the opening decision under this policy for each firm in each period is optimized with consideration to its impact on price and, therefore, the profitability of other firms, the value of delaying and the potential competitive responses of its competitors. Indeed, in our simulation of 10 runs, the best firm-NPV policy yields at least 30% better cash flow NPV than the positive-mine-NPV policy. On the other hand, the best-firm-NPV policy outperform the positive-firm-NPV policy too, but not as significantly—the cash flow NPV of the best-firm-NPV is around 6% more than that of the positive firm-NPV policy.

While the best-firm-NPV policy and the positive-firm-NPV policy have similar NPV for each firm under the base case, the price and output paths of the market under the two policies diverge greatly. As can be seen in the price vs. quantity graph in Figure 6, the price under the best-firm-NPV policy grows from $47 at the beginning to around $51 by the end of the 27 year simulation, but stays at $47 with occasional dips to as low as $44 under the positive-firm-NPV policy. This is due to the opening of 7 new mines under the latter policy compared to 4 under the former. On the other hand, the market annual output reached by the end of the periods under the positive-mine-NPV policy is 10% more than that under the best-firm-NPV policy, despite the same secular demand growth under both policies, as a result of the increased demand due to lower price. Despite two divergent growth patterns, the NPV of the firms under the two policies are similar (within 6%), as the increased output under the positive-firm-NPV policy is largely sufficient to make up for the lower profit margin.

Hence, in this base case scenario, without significantly sacrificing corporate NPV, the less sophisticated positive-firm-NPV decision policy generates higher market output while keeping the price low and steady compared to the two alternative decision-making methods. From a policymaker’s perspective, it might be a more favorable investment decision-making method than the more sophisticated best-firm-NPV one, since this combination of high output and lower price with strong profit to the firms would offer cheap materials for downstream economic
activities while keeping the commodity industry's economics healthy. On the other hand, extracting more resources and providing them at lower prices might generate more significant environmental and resource depletion impacts, leading regulators who seek to minimize resource depletion while maintaining the profitability of this mining market to prefer that firms adopt the dynamic game strategic investment decision model.

**Turnover and Market Share Impact**

Besides the bottom-line NPV, firms are also concerned about their topline financial outcome, i.e. turnover, as well as their share of the market, which are illustrated in Figure 8 and Figure 9 respectively below. The overall market turnover, presented in Figure 8, is the lowest under the positive-mine-NPV policy and highest under the best-firm-NPV policy, although the latter is very similar to the market turnover under the positive-firm-NPV policy. In the last five periods, however, the positive-mine-NPV and positive-firm-NPV turnover slightly exceeds the turnover under the best firm-NPV policy, because, due to continued demand growth, the additional volume opened under the first two policies is now sufficiently makes up for its negative price impact. This ranking of investment decision methods by the turnover metric is consistent with their ranking by the cash flow NPV metric already discussed.

![Figure 8: Market turnover in each period for different policies](image)

In terms of market share, each decision method produces a different set of winners and losers depending on the specific mine opening decisions, although the change in market share for any
one firm does not exceed 3 percentage points. The most salient pattern in the change in market share is that the best-firm-NPV policy, which has the best cash flow NPV outcome out of the different decision policies, leads to a slightly lower market share for the three major firms (from 61.8% to 61.6%), whereas the worse-cash-flow-NPV-outcome positive-firm-NPV and positive-mine-NPV policies lead the major firms to end up with 67% market share at the end of the simulation. The loss in market share under the less expansionary best-firm-NPV policy is due to the firms not expanding as much as the increase in demand, which led to more production by the ROW mines that are higher on the existing supply cost curve. Under the other two decision paradigms, the major firms expand more aggressively, precluding the operation of higher-cost ROW mines and ending up with a larger market share.

Figure 9: Market share of the firms and of the rest of the world (ROW)
4.2.3 Cartel in the Base Case

One of the policies discussed throughout the different scenarios analyzed above is the cartel policy, which seeks the jointly-optimal decision that maximizes the total NPV of the three major firms, assuming that they can collude with binding promises. In the base case, forming a cartel and colluding to open fewer mines results in not only higher NPV overall by 4%, but also a 3-4% increase in cash flow NPV for all three individually, making it both individually desirable and collectively feasible. The desirability and feasibility of forming a cartel might be different under different demand and supply conditions, as we will examine in below scenario analyses.

![% Cashflow NPV improvement with collusion](image)

Figure 10: Cash flow NPV improvement (%) of the cartel policy (collusion) vs. best-firm-NPV policy (non-collaboration) in base case scenario

4.3 Dynamics under Different Demand Conditions

4.3.1 Growth Rate and Pattern

As the optimization of the firms' decision rules is based on a fixed underlying demand growth pattern that is presumed to be known accurately by the firms at the beginning of the periods, the demand growth pattern might have a substantial impact on the impact of using more sophisticated investment paradigms.

There are two aspects of growth patterns we are examining: what happens when the overall demand growth over the 27 years does not change, but the pattern of growth changes, and what
happens when the overall demand growth rate changes (but the pattern does not). To examine the impact of different demand growth patterns and rates, we compare the results of the model under the following twelve demand growth scenarios to one another and to those under the base one of 1% annual growth. The two sets of demand scenarios are illustrated in the figures below. Please find in the appendix the detailed description of the scenarios.

**Figure 11:** Demand scenarios for testing impact of growth rate

**Figure 12:** Demand scenarios for testing impact of growth pattern
Impact of Growth Rate

One salient feature of the results of the simulation is that the range of NPV from the 10 different actualizations of demand perturbation is tighter when the demand growth is positive and especially when it reaches 2%. This means that temporary demand perturbations, even at the same percentage magnitude, have less impact on the profitability outcome of the firms when the demand is growing faster, and hence the corporate decision-makers have less need to take potential but temporary demand shocks into account when the market demand is growing faster.


As shown in the NPV charts in Figure 13, at negative and zero demand growth, whether the firm opens new mines based on net positive NPV for the mine for the firm as a whole result in nearly the same cash flow NPV for all the firms regardless of their supply cost or incentive mine cost positions. The additional firm-level consideration for the impact of new mine openings on the profitability of existing mines does not generate any profit payoff. However, when demand grows, even moderately, thinking only about the mine NPV leads to at least 20% worse NPV results for every firm. Considering investment decision's impact on the whole firm is more important when demand grows. This is because the expectation of higher demand in the future prompts more and earlier mine opening under the positive-mine-NPV paradigm than under the positive-firm-NPV paradigm. Due to the shape of the supply curve and the position of the current marginal supplier, an aggressive opening schedule under increasing demand leads to more profit decrease in existing mines than the profit generated by new mines, making aggressive expansion less favorable under the positive-firm-NPV decision paradigm than positive-mine-NPV decision paradigm.

As for the dynamic game theoretic best-firm-NPV policy, our intuition would suggest that its cash flow NPV performance would not be as different from the non-game-theory positive-mine-NPV and positive-firm-NPV policies under higher demand growth, because the demand growth would lessen the price impact of opening. The results from the simulation, however, conform only partially to this intuition.
First, let’s compare the cash flow NPV performance of the best-firm-NPV policy against the simplest base policy of positive-mine-NPV policy in the simulation. In negative and no-growth scenarios, the best-firm-NPV policy outperforms the positive-mine-NPV policy by 15-25%, as expected. For positive demand growth (especially when exceeding 0.5%), contrary to our intuition, the cash flow NPV gap between the game theory policy and the base policy of positive-mine-NPV increases to 20-45%. This suggests that making decisions using a firm-level impact view, incorporating game theory and considering all the potential branches of decisions and states in the future become even more important when demand is growing.

The above counter-intuitive conclusion is less true when the simulation cash flow NPV from the best-firm-NPV policy is compared against those from the positive-firm-NPV policy. In negative and no-growth scenarios, the best-firm-NPV policy still outperforms the positive-mine-NPV policy by 15-25%, as expected. In moderate growth scenarios (0.5%-1.5%), the positive-firm-NPV policy catches up to the best-firm-NPV policy in cash flow NPV performance, and even exceeds it in the 0.5% growth scenario as a result of delayed openings compared to the best-firm-NPV policy, as seen in Figure 14. This aligns with our intuition that game theory is less important when demand grows more. However, when demand rate increases to 2%, the best-firm-NPV policy once again performs significantly better than the non-game-theory positive-firm-NPV one, though this time by a smaller margin of 10-15%.

It is a little counter-intuitive to see the positive firm-NPV policy generate more delayed openings under 0.5% demand growth compared to no demand growth, since a mine opening that is positive in NPV when demand is not expected to grow should still be positive when demand is expected to grow. The decision policy behaves this way because the positive-firm-NPV policy sometimes anticipate more openings by other firms in the future when demand grows slightly more, resulting in more negative price and profit impact on its existing mines if it were to open now, hence it defers the decision to open a new mine to a later time. However, the positive demand growth is generally sufficient to compensate for this effect of incentivizing more competitors to enter, as we can see in the other growth rate scenarios in Figure 14, leading to generally more and earlier opening under the positive-firm-NPV decision paradigm when demand is growing faster.
Collaboration vs Non-collaboration among the Major Firms

Regardless of the growth rate, the optimal cartel policy is for firm A to open up mine A1, and no other mine openings. Under this course of action, the total NPV of the three major firms is maximized. If the firms were not able to collaborate and instead tried to maximize their individual NPV while considering other firms' potential actions (i.e. the best-firm-NPV policy), when the demand growth rate is zero or negative, fewer mines would open and only the ones with lower overall costs. When there is positive demand growth and as the growth rate increases, it becomes favorable for other higher cost mines to open as well. However, the amount of new mine volume opening does not always increase when the demand growth rate increases (see the mine opening decisions under 1% and 1.5% demand growth in Figure 14). This is because as demand grows and price increases, demand could experience a permanent downshift as a result of price-driven substitution away from the mineral.

When the demand growth rate is zero or negative, because of the similar optimal mine opening decisions in the non-collaborative best-firm-NPV policy and collaborative cartel policy, the NPV under the two policies are very similar for all the firms. Despite more mines of each firm opening under the non-collaborative policy, the higher price resulting from the cartel policy offsets the additional new volume from the non-collaborative policy. At positive demand growth rates, Firm B and C enjoy slightly higher cash flow NPV under the cartel policy than the non-collaborative policy whereas Firm A enjoys a more significant boost from the major players acting as a cartel, because it is the only firm that opens up any new mine in order to maximize joint cash flow NPV under the cartel policy.
Figure 13: Firm NPV (Normalized so that positive-mine-NPV policy=100) under different demand growth scenarios
Figure 14: Mine opening decisions and production quantity under different demand growth rate\(^9\)

\(^9\) From top to bottom of each graph, the policies presented are: best-firm-NPV policy, positive-mine-NPV policy, positive-firm-NPV policy, and cartel policy
Impact of Growth Pattern

It is to be expected that growth rate would matter for the path taken by the market and the firm performance under the different mine opening policies. They not only affect the demand level in each period and also lead to fundamentally different demand conditions at the end of the periods. What if the overall growth rate of the market demand is the same over this period, but a different path shape is taken to reach the end demand level (as depicted in Figure 12)? In this section, we explore the impact of the pattern of demand growth on mine opening decisions and performance of different policies.

Intuitively, more mines would be expected to open earlier if the rate of growth was faster in the period closer to the present, because its effect on raising price and hence overall profit would be larger in terms of NPV due to less time discounting. However, the increased early opening might result in reduced overall cash flow because when demand growth slows down or decreases later, the more mines opened earlier might lead to a lower NPV in later periods. The over-expansion problem for fast-slow growth pattern might be especially problematic for the positive-mine-NPV and positive-firm-NPV policies that respond to higher growth rate in the earlier periods with more early openings than the best-firm-NPV policy (as Figure 14 of the previous section shows, an increase in demand growth rate leads to a higher increase in the number of mines opened under the positive-NPV policies than the game theoretic best-firm-NPV policy).

In the simulations of both the growth-decline vs. decline-growth scenarios (Figure 16) and fast-slow vs. slow-fast growth scenarios (Figure 15), the intuition that an earlier period of higher growth followed by a later period of slower or even negative growth generates more mine openings earlier is true under all policies (except the cartel policy, where one mine opens regardless of growth pattern). This is because a higher demand would have a larger positive impact on the NPV and hence more incentive to open a new mine when the higher demand occurs in earlier periods (because of less time discounting).

In terms of the favorability (measured by cash flow NPV) of using one investment policy versus another under the different growth rate patterns, the results are more complex and sometimes against the intuition discussed above. Unlike what we might expect, the best-firm-NPV policy seems to generate even more cash flow NPV benefit versus the base policy of positive-mine-
NPV policy when the demand growth pattern is slow-fast and decline-growth rather than the opposite scenarios. However, a large portion of the better performance in the slow-fast and decline-growth scenarios might not be due to the dynamic optimization of the NPV and the game theory considerations, but rather the expansion in consideration of the impact of new mine openings from just the new mines themselves to the firm level. The addition of the game theory and NPV optimization components do not make any difference in how much better the cash flow NPV of the best-firm-NPV policy is compared with the positive-firm-NPV policy under the two opposing sets of demand patterns. However, by adopting a firm-level cash flow NPV outlook, the positive-firm-NPV policy outperforms the positive-mine-NPV base policy by a larger percentage under the slow-fast or decline-growth scenarios compared to the opposite scenarios.

The undiscounted cash flow graphs in Figure 15 and Figure 16 further reveal how the annual cash flow (adjusted by capex amortized as a perpetuity) of the different policies track each other and diverge under the two sets of demand patterns. The positive-firm-NPV eventually converges with the positive-mine-NPV in all demand pattern scenarios. However, in the fast-slow and growth-decline scenarios, they converge faster than in the slow-fast and decline-growth scenarios, causing bigger difference between the cash flow NPV of the policies in the latter scenarios. Although best-firm-NPV tracks the positive-firm-NPV cash flow path closely in the earlier periods for both sets of demand patterns, the best-firm-NPV outperforms the latter significantly when demand growth is fast-slow and growth-decline but continues to track the positive-firm-NPV policy closely in later periods under the decline-growth scenario (and to a lesser extent the slow-fast scenario), accounting for the larger advantage of the game-theoretic best-firm-NPV policy over the positive-firm-NPV policy in the fast-slow and growth-decline scenarios.
Slow-then-fast growth pattern

NPV Comparison (normalized)

<table>
<thead>
<tr>
<th>Firm</th>
<th>No new opening</th>
<th>Best firm-NPV policy</th>
<th>Positive-mine-NPV policy</th>
<th>Positive-firm-NPV policy</th>
<th>Cartel policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<tr>
<td>B</td>
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<tr>
<td>C</td>
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</tbody>
</table>

Fast-then-slow growth pattern

NPV Comparison (normalized)

<table>
<thead>
<tr>
<th>Firm</th>
<th>No new opening</th>
<th>Best firm-NPV policy</th>
<th>Positive-mine-NPV policy</th>
<th>Positive-firm-NPV policy</th>
<th>Cartel policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>B</td>
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<tr>
<td>C</td>
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</tbody>
</table>
Figure 15: Slow-fast vs Fast-slow demand growth pattern: Cash flow NPV, opening decisions, and capex-adjusted cash flow over time (vs positive-mine-NPV policy)
4.3.2 Volatility

Although the underlying demand for all of the periods in the model is pre-known and fixed, in each period, demand perturbation of known and fixed probability is realized in the market after all three firms make a new mine-opening decision. In the base case, the demand perturbation amplitude is set to 0.05, which correspond to the following possible demand after the perturbation is realized:

\[
\begin{align*}
D_{\text{high}} &= (1 + 0.05) \times \text{underlying demand} \\
D_{\text{no shock}} &= \text{underlying demand} \\
D_{\text{low}} &= (1 - 0.05) \times \text{underlying demand}
\end{align*}
\]
In the base case, the probability is (0.1, 0.8, 0.1), which corresponds to the probability of \( D_{\text{high}} \), \( D_{\text{no shock}} \), \( D_{\text{low}} \) respectively. The expected underlying demand is the same as the demand in the no shock case due to symmetry of the shock amplitude and probability.

Conceptually, perturbation of demand would affect investment strategy because it affects the payoff from opening a mine, not only in the current period but in future periods because of some amount of hysteresis in the demand path. Both the probability and magnitude of perturbation might affect the optimality of the strategy, because the positive-mine-NPV and positive-firm-NPV based methods account for perturbation in a different way.

In literature, increased volatility is thought to increase the value of real options, and hence we’d expect the more dynamic optimization method to perform better than the positive-firm-NPV and positive-mine-NPV methods by a wider margin in case there is a larger magnitude or more probability of perturbation.

We examine this hypothesis by running a 100-run Monte Carlo simulation of the market evolution under three different perturbation parameters and two different probability distributions. As Figure 17 illustrates below, as the magnitude of the demand perturbation is increased to 0.15 and beyond, the cartel policy and the best-firm-NPV policy overlap in decision and NPV outcome as fewer mines open under the best-firm-NPV policy. Hence, as the demand shock of the market increases and reaches a certain level, the market would have fewer openings and reach the monopoly market outcome when the three major firms make decisions based on the maximization of firm NPV and consider one another’s strategic responses. The positive-firm-NPV and positive-mine-NPV policies are not affected by the change in perturbation because they are based on expected NPV calculated from the expected demand in each period, which remains the same. In terms of realized performance of the different policies, due to the increase in perturbation magnitude, the NPV outcomes of the different policies in aggregate overlap more, although they are still distinct as before for any single realization of the market.
Base case
perturbation 0.05,
probability 0.1, 0.8, 0.1

perturbation 0.15,
probability 0.1, 0.8, 0.1

perturbation 0.20,
probability 0.1, 0.8, 0.1

Figure 17: Distribution of NPV under different probability magnitude (100 runs)
Figure 18 illustrates what happens to the NPV of the different firms under different policies if the likelihood of perturbation is increased but not the magnitude. When the likelihood of perturbation in each direction is increased from 10% to 20%, the relative performance of the policies do not change significantly, besides a slight worsening of the best-firm-NPV policy cash flow NPV for Firm C and improvement in the positive-firm-NPV policy cash flow NPV for Firm C and A. When the perturbation likelihood is increased further to 30%, all of the policies experience a downward shift in their expected cash flow NPV for all the firms. Furthermore, whereas the best-firm-NPV policy over-performed the positive-firm-NPV policy in cash flow NPV in the 10% and 20% perturbation likelihood cases, it now underperforms the positive-firm-NPV policy for Firm A. The best-firm-NPV policy becomes less advantageous for A, the best cost position firm, when the perturbation likelihood increases.
Figure 18: Distribution of NPV under different probability distribution (100 runs)
4.3.3 Price Elasticity of Demand

In the base case, the price elasticity of demand, which reflects the short-run change in quantity demanded in response to price, is set to be relatively inelastic (0.5) due to the finding in literature that the short-run elasticity of demand for many minerals is inelastic due to it being a small component of the final product cost and sometimes the difficulty of substitution (Johnson, 1956). Literature suggest that while the short-run elasticity of demand for many minerals is inelastic (Tilton, 1992), it varies widely depending on the availability and difficulty of substitution (Stuermer, 2013). This section examines whether and how the firms’ optimal decision-making method changes when facing a market of a different level of price elasticity of demand by comparing the firm and market outcomes at price-elasticity of demand of 0.5 (base level), 0.75, 1, 2, and 0.1.

Figure 19 shows the firm NPVs in decreasing price elasticity of demand. As demand becomes more inelastic, the static decision paradigms (positive firm-NPV and positive mine-NPV) generate worse outcomes compared to the dynamic best-firm-NPV policy. When demand is very elastic at elasticity of 2 (i.e. very responsive to price), there is little difference between the decision paradigms. The reason behind this phenomenon (illustrated by the price-quantity evolution graph in Figure 20) is two-fold. First, higher elasticity has a negative dampening effect on the market quantity and price under the less expansionary policies (i.e. best-firm-NPV and cartel policies). A more elastic demand means that when the price climbs higher as demand increase outstrips supply expansion, there is a negative impact on the quantity. Hence, when the price increases under the less expansionary policies, the volume traded in the market is neither as high nor for as high a price as when the demand is more inelastic. Second, a more elastic demand would dampen the negative price impact caused by supply injection with more demand volume increase due to the lower price, hence making policies where there are more new openings (i.e. the more expansionary positive-firm-NPV and positive-mine-NPV policies) more favorable.

This intuition is borne out by an examination of the new mine opening decisions under the different elasticity parameters. The more elastic the demand, the more mines open under the best-firm-NPV policy (as well as the cartel policy). Opening decisions under the positive-mine-NPV and positive-firm-NPV policies, on the other hand, are not heavily affected because seven of the mines would already open even when the price were inelastic. Even for these two policies,
more demand elasticity results in more concentrated mine openings at the beginning of the period instead of waiting till later periods of higher demand, and the reason is the same as before – the price effect of flooding the market with new supply is dampened.

Figure 19: Firm NPV under different price elasticity of demand
Figure 20: Price-Quantity path under different price elasticity of demand. More elastic demand dampens the impact of supply volume injection.
4.4 Impact of Supply Structure on Optimality of Decision Paradigms

4.4.1 Market Competitive Structure and Relative Cost Positions of the Major Firms

Because the base scenario market is constructed based on the features of a real mineral market, the three major firms have existing and incentive mines of different quantities and cost, as they would in real life. While the use of heterogeneous supply and cost structure enable us to analyze a market that is more realistic, it begs the question of how much of the outcome is dependent on the specific market structure itself, especially the cost position and market strength of the different players.

To examine how the relative performance of the different investment paradigms might change if the supply structure were different, a set of artificial supply and incentive supply curves were constructed by modifying features of the base supply curve. In order to isolate the impact of the feature modified, the other features (such as total supply, range of prices, shape of supply curve) have been kept as similar to the base situation as possible. The supply situations are described and depicted in Table 2. Overall, we are examining the impact of having differential versus identical incentive price or cost positions for the major firms in the market, as well as the impact of having more market power for the major firms.
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base supply</td>
<td>The base scenario based on a real mineral market</td>
</tr>
<tr>
<td></td>
<td><strong>Base supply</strong></td>
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<tr>
<td></td>
<td><img src="image" alt="Base supply" /></td>
</tr>
<tr>
<td></td>
<td>Base supply with more concentration</td>
</tr>
<tr>
<td></td>
<td>This is the base supply curve with each mine of the majors and the ROW scaled up and down respectively to allow the majors to have 60% instead of 42% of the market share. The total volume of the existing supply is unchanged. The incentive mines are also scaled up in their volume to maintain the previous ratio with the existing mines of the major firms, which means the total incentive mine volume has increased from the base supply.</td>
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<tr>
<td></td>
<td><strong>Base supply with more concentration</strong></td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="Base supply with more concentration" /></td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
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</tr>
<tr>
<td>Base supply with more concentration but no incentive curve changes</td>
<td>This is almost the same scenario as the Base Supply with More Concentration. However, the incentive mines are not scaled up, in order to maintain the same total amount of the incentive mines available as the base supply so that opening any single mine has the same volume impact on the market as before. On the other hand, the incentive mines are now less significant compared to the existing volume of the majors, hence opening a new mine would bring less benefits to the firm that owns it than before, reducing the desirability of opening up new mines.</td>
</tr>
<tr>
<td>Equal supply position</td>
<td>The existing supply curves of the three major firms are adjusted to be identical by dividing the existing overall market share of the major firms equally among the firms and making each have the same number of mines and cost positions. Each firm’s supply curve follows the shape of firm C, because C has the widest range of opex for existing mines and hence provides the most interesting supply setting for examining impact of different strategies in opening new mines. The overall shape, number of existing mines, and total volume of the existing supply curve are not affected. The capex per unit, opex, and production volume of the incentive mines are changed to be the same for each tier of mines across the three firms, while the number, total incentive production volume and the range of capex and opex are kept the same as the base case.</td>
</tr>
</tbody>
</table>
Equal supply with more concentration

This is the same as the Equal Supply Position scenario but instead of the majors together taking up 42% of the market, they now take over 60% of the market. The effect is achieved by scaling each existing mine of the majors and scaling down those of the ROW accordingly. The incentive mines are similarly scaled up in their volume to maintain the previous ratio with the existing mines of the major firms.

Table 2: Summary of supply scenarios examined
4.4.2 Impact of Greater Market Concentration

**Base Supply with More Concentration**

When the base supply scenario is modified to increase the market share of the three major firms by 50% (from 40% to 60% of the total market), the optimal policies under all investment paradigms have fewer openings by Firm B and C because the now larger size of the major firms’ mines, which tend to cluster at the lower half of the supply curve, pushes the higher-cost incentive mines of B and C into the uneconomical supply realm at the same level of demand. Consequently, the NPV difference between all three of the non-collaborative policies (the best-firm-NPV, positive-mine-NPV, and positive-firm-NPV policies) diminishes significantly. On the higher concentration scenario, the firm-based decision paradigm only improves the NPV of the firm cash flows by 5-6% over the mine-based decision paradigm, compared to 25-27% in the base supply scenario. The game theoretic best-firm-NPV policy results in only 9-13% increase in NPV compared to the mine-based paradigm, compared to 35%-38% in the base supply scenario case (see Figure 21). The use of the more sophisticated investment decision methods does not seem to improve the outcome of the decision as significantly when the market is more highly concentrated in the hands of the major firms. One reason may be that as the major firms which generally have lower costs gain market share, the lower cost portion of the supply curve expands, the price at the same demand becomes lower, and new mines are less incentivized to enter. Hence, under the mine-NPV-policy new mine expansion becomes less aggressive when the market is more concentrated in the major firms. By the same logic, the two firm-NPV-based policies also contain fewer new mine openings. In this specific market structure, new mine openings under the positive-mine-NPV-based policy is sufficiently discouraged by the increased major firms’ size that the NPV performance gap among the different decision paradigms is smaller. Further study needs to be done to explore how the behavior is different if the major firms’ gain in market share comes from only expanding higher-cost mines instead of expanding all existing major firm mines.
Figure 21: Normalized cash flow NPV under different policies for base supply scenarios with and without more market concentration of the major firms
Due to the same reason, when the major firms take up more market share and the market becomes more concentrated, forming a cartel and making decision together significantly outperforms the firms acting non-collaboratively. Collusion has a higher payoff than each firm making its own decisions based on the game theoretic best-firm-NPV policy when the major players own a larger share of the market. As the graphs show in Figure 21, the higher collusion payoff with more market concentration is true regardless of which option we take in modifying the volume of the incentive mines to correspond with the larger size of the existing major firms' mines -- whether to keep the major firms' incentive supplies constant in size relative to the majors' existing mines (hence larger with respect to the total existing supply), or to keep their size constant relative to the total existing supply (hence smaller compared to the firms' existing mines). The new mine opening decisions that yield the optimal cartel cash flow NPV stays roughly the same – only Firm A opens up one mine, and none in the scenario with more concentration but no incentive curve change (see Figure 21). However, while Firm B and C previously opened mines under the best-firm-NPV policy in the base supply curve scenario, they no longer do so under the more concentrated supply scenarios. This is a result of the flattening of the supply curve induced by the volume increase in the major firms' generally lower-cost mines, which causes Firm B and C's higher cost incentive mines to no longer be attractive to open. As a result, the increase in payoff of collusion vs non-collaboration is most significant for Firms B and C, but relatively small for Firm A.

*Equal Supply with More Concentration*

The fewer openings of Firm B and C in the optimal policy under all investment paradigms in the more supply concentration scenario, which results from B and C's higher cost positions than A on the supply curve, fundamentally drive both of the phenomena discussed above. If Firms B and C had lower cost incentive mines that would still be attractive on the new flatter supply curve like Firm A, Firms B and C would not open up fewer mines in the optimal policy under the different investment paradigms. In such a case, the observed lessening of cash flow NPV advantage of the more sophisticated paradigms and the rise in advantage of collusion in the more concentrated supply scenario would presumably disappear.

We test this hypothesis in this section by comparing two scenarios where the firms have symmetric cost positions in existing and incentive supply, but where the major firms occupy
40% and 60% of the market, respectively. As discussed in the supply scenario construction section, the “equal supply position” and “equal supply with more concentration” scenarios have been constructed based on the “base supply” scenario to preserve the overall shape, number of existing mines, and total volume of the existing supply curve, but to divide them equally among the three major firms.

<table>
<thead>
<tr>
<th>Equal supply position scenario</th>
<th>Equal supply with more concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="NPV Comparison (normalized)" /></td>
<td><img src="image2" alt="NPV Comparison (normalized)" /></td>
</tr>
<tr>
<td><img src="image3" alt="New Mine Openings - Capacity Added vs Market Quantity (ABC)" /></td>
<td><img src="image4" alt="New Mine Openings - Capacity Added vs Market Quantity (ABC)" /></td>
</tr>
</tbody>
</table>

Figure 22: Cash flow NPV and mine opening decisions in equal supply scenarios - original vs more market concentration

As Figure 22 illustrates, when the three major firms are identical (hence all have an incentive mine as cheap as the cheapest mine of Firm A) and take up 60% instead of 40% of the market
share, the more sophisticated paradigms are as advantageous over the baseline positive-mine-NPV paradigm as in a market with less concentration. This conforms to the hypothesis.

However, in contrast to the hypothesis, the value of forming a cartel and colluding on investment decision is higher (and in this case, higher for all firms instead of just B and C) when the market share is more concentrated in the major firms. The superiority of collusion when the market share of the major firms is higher is true in these equal supply position scenarios as it was in the base supply scenarios discussed in the previous section, despite different supply curve shapes and relative strengths of the firms, suggesting that the incentive to collude might be larger when the market is more dominated by the three large players, regardless of how the market and cost positions of the three players compare. This could be because when the major players are larger, they also have more existing production volume, hence more negative impact from any new mine openings. Hence, colluding to not only up as many new mines would produce a higher profit payoff. This speculation would need further testing with other supply configurations, which is beyond the resource of this thesis and could be done in future work.

4.5 Role of Decision Ordering on Competitive Dynamics

4.5.1 Real-Life Relevance of Decision Ordering

Although decision ordering is mainly a feature born out of model implementation needs in order to solve for a unique Nash equilibrium for game-theory based best-firm-NPV policy, it nevertheless has real-life relevance.

In oligopolistic markets, the timing of when one firm commits to an expansion decision relative to other firms might affect its competitive outcome when firms act in a game theoretic fashion. Literature has shown that, in a real options game of supply quantity decisions, players could enjoy first mover advantage when the “strategic effect” of early overinvestment is positive – i.e. when the entry of rivals produces negative externality for existing firms and early overinvestment could successfully preclude entry by the rivals (Chevalier-Roignant et al., 2011; Haque et al., 2014; Murto et al., 2004). Under other circumstances (e.g. negative strategic effect, high price uncertainty), being the first to move could be a disadvantage, as the later players could react to the initial player’s decisions and evolving market conditions and optimize their
decisions, whereas the first player could only make its decisions imperfectly based on the decisions that it expects other players to make (Chevalier-Roignant et al., 2011).

4.5.2 Factors Affecting the Importance of Decision Ordering to Market Outcomes in a Mining Capacity Expansion Game

In the market expansion game constructed (i.e. when all the firms make decisions under the best-firm-NPV paradigm), is there also an advantage or disadvantage to being the first actor who is able to commit to a supply expansion decision?

One hypothesis is that the size of the influence of decision ordering in the game on the final outcome depends heavily on whether the cost positions (both existing and incentive) of the firms differ significantly. The more homogenous the firms, the more the order of decision-making might translate into advantage or disadvantage to the different players. However, when firm cost positions are highly distinct and especially when one has a significant cost advantage over all other firms (in the base case, this would be Firm A), whether the lowest-cost firm goes first or last would probably not matter. This is because if it is always favorable for the lowest-cost player to open regardless of other players’ decisions, then the other players might be sufficiently disincentivized by this expectation of higher volume and lower prices to be less aggressive in mine opening, regardless of who makes the expansion decision first.

In addition, how much ordering would matter to the decisions made in the market and the firm cash flow outcomes might also depend on how significantly the players’ incentive mines could impact the market given their opex position and volume. The larger production volume the firms’ incentive mines have, the more we could expect them to affect the market price with their opening decisions and therefore the order they get to potentially open might matter more.

To examine the impact of cost position and market importance on the significance of expansion decision-making ordering, we analyze the impact on ordering on two different supply scenarios: 1) base supply scenario; 2) equal supply position scenario; and 3) the equal supply with more concentration scenario (which we consider in conjunction with the equal supply position scenario because both have symmetric firms). The base supply scenario has heterogeneous firms in which A has a very cheap mine that tends to produce even during the most expansion-disciplined cartel
policy. The equal supply position scenario would show the pure impact of ordering and examine whether the homogeneity of firms have an impact on the importance of the order of decision making in a three-player game of capacity expansion.

The evaluation of the impact of decision-making ordering under different supply structures will be based primarily on how it affects the number, identity, and timing of the mines openings under the different policies as well as the cash flow NPV. Only the best-firm-NPV investment paradigm is examined, since it is the only policy that incorporates game theoretic considerations of potential future competitive response to one’s expansion actions and, hence, is the only relevant policy to examine the hypotheses regarding decision ordering and first mover advantage.

4.5.3 Examination of Impact of Decision Ordering under Different Supply Scenarios

_base supply scenario_

Figure 23: Cash flow NPV outcome (individual firms and in total) of the best-firm-NPV policy under different decision ordering for the base supply scenario

In the base case of heterogeneous firms, change in the order of decision-making leads to appreciable difference in the optimal mine opening decisions and the firm cash flow NPV outcome (illustrated in Figure 23 and Figure 24), despite our attempt to minimize the impact of
decision ordering in this modeling by giving every firm the choice to open in every period and eliminating any period where the first mover might enjoy protection from entry by its competitors.

In terms of the magnitude of the difference in outcomes, the different orderings create at most +/- 4% difference in terms of cash flow NPV for each of the firm, which is significant but small. There does not seem to be a clear disadvantage or advantage to being in any of the positions. However, there are some sequences that provide better outcome for all firms. The best ordering, Firm C-Firm B-Firm A (CBA), is distinctly advantageous for all and leads to at least 4% better cash flow NPV than all the other orderings for all three firms. The reason that the CBA decision ordering produces a better cash flow NPV outcome for all three firms is that only one mine of A and none else open under the expected-firm-NPV maximizing game theoretic equilibrium produced by this specific decision making order. The scarcity of new mines opened stands in contrast to the four mines (two of A, one of B, one of C) that open under each of the five other orderings, as shown in below. The second most favorable decision ordering, from the perspective of both the major firms overall and individual firms, is ABC, where A opens one mine and the other three mines do not open before period 10, hence delaying the negative price impact of new volume on the market.

<table>
<thead>
<tr>
<th>Decision ordering</th>
<th>Mine opening decisions under the optimal policy of the best-firm-NPV investment paradigm (base supply scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td><img src="image" alt="Graph of Mine opening decisions for ABC" /></td>
</tr>
<tr>
<td>ACB</td>
<td><img src="image" alt="Graph of Mine opening decisions for ACB" /></td>
</tr>
</tbody>
</table>
Figure 24: Optimal mine opening decisions under the different decision orderings (base supply scenario)
Equal Supply Position Scenario (and Scenario with More Concentration)

Equal Supply Position Scenario
% Difference vs. ABC Ordering

Figure 25: Cash flow NPV outcome (individual firms and in total) of the best-firm-NPV policy under different decision ordering for the equal supply position scenario

In the case of equal supply positions across the three firms, the cash flow NPV outcome is the same for all firms regardless of the decision ordering. In the mine decisions of the optimal policy under this investment paradigm and supply condition, each firm opens up its cheapest mine in period 1, but nothing else for the rest of the time. The symmetry in the optimal opening decisions and in the firms’ supply conditions make ordering of decision-making irrelevant.

With more of the market concentrated in the hands of three major firms, the optimal policy under the best-firm-NPV scenario yields mine opening decisions for the three firms that are no longer symmetrical among the firms, even though their existing and incentive supply positions are still identical to one another.

As can be seen in Figure 26 below, all orderings have the same cash flow NPV in total, but distributes them differently among the firms depending on the decision ordering. When the optimal decision in the equal supply scenario is no longer for each firm to open a mine in the same period, but to open four mines over three periods, the order in which the firms are able to make their decision affects the cash flow NPV outcome by +/-10%. This is substantially larger.
than the +/-4% for the base supply scenario where the firms are heterogeneous, and supports our initial hypothesis that the more homogeneous the market, the more decision ordering matters, with the significant caveat that the volume-price tradeoff of opening up in the same period for all three firms should not be favorable enough in terms of the cash flow NPV to be the optimal policy. The overarching assumption for this hypothesis to be applicable is that the new mines that have significant scale relative to demand so that they do influence price if they enter. Otherwise, if the new mines are small, none of the firm-level or strategic considerations are likely to matter.

However, not all decision ordering changes result in changes in the distribution of profits among the firms. As seen in Figure 26, ABC and BAC have the same profit distribution (C has 10% less cash flow NPV than the other two firms); ACB and CAB have the same profit distribution (B has 10% less cash flow NPV); CAB and CBA results in A having 10% less cash flow NPV. There is a distinct and significant profit disadvantage to being the last decision-maker in this supply scenario because, by opening their cheapest incentive mine during the first period, the first two firms to make decisions effectively pre-empt the possibility of the third firm to open in the same period because the resulting price depression would generate a net profit loss for the third firm in spite of the extra volume. Even though the third firm then open up two mines, including the cheapest mine, in period 4 and 6 (as seen in Figure 27), the extra volume is not enough to make up for the profit gap between the third firm and the first two firms in the initial periods, when the third firm did not have new volume opened.
Figure 26: Cash flow NPV outcome (individual firms and in total) of the best-firm-NPV policy under different decision ordering for the equal supply more concentration scenario.
<table>
<thead>
<tr>
<th>Decision ordering</th>
<th>Mine opening decisions under the optimal policy of the best-firm-NPV investment paradigm (equal supply position scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABC</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>BAC</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>ACB</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>CAB</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>BCA</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>CBA</td>
<td><img src="image" alt="Graph" /></td>
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</tbody>
</table>

Figure 27: Optimal mine opening decisions under the different decision orderings (equal supply more concentration scenario)
4.6 Inter-Firm Collaboration: a Real Threat?

4.6.1 Incentive to Collude: Cash Flow NPV Enhancement (or Lack Thereof) under Different Market Structure and Conditions

One of the policies discussed throughout the different scenarios analyzed above is the cartel policy, which seeks the jointly-optimal decision that maximizes the total NPV of the three major firms, assuming that they can collude with binding promises. In the base case, forming a cartel and colluding to open fewer mines results in not only higher NPV overall by 4%, but also increases by 3-4% the cash flow NPV for all three individually (see Figure 10), making it both individually desirable and collectively feasible.

The analysis of the relative NPV outcome for each firm under the collaborative cartel policy and the non-collaborative best-firm-NPV policy shows that under some market structures and conditions, the three major firms have an incentive to collude to open fewer mines in order to obtain a higher cash flow NPV for the three firms overall and for some, often all, of the firms individually. Under other conditions, the firms would not collude because the non-colluding outcome is the same as the one for colluding due to interaction of game theory considerations by the firms and the structure and conditions of the market. The detailed results were discussed in the relevant scenario analysis sections above. The key findings on the appeal of collusion are summarized below.

In terms of how demand growth affects cartel desirability, when the growth rate is higher, it is more favorable for all firms to engage in cartel behavior, because the higher demand levels lead to a greater profit payoff to disciplined supply expansion as the market moves to the steeper part of the supply curve (where small changes in supply have substantial influence on price). In terms of demand growth patterns, when the demand grows overall at an average of 1% per year, it is more favorable for almost all firms to participate in the cartel, causing the overall cash flow NPV for the three firms to collectively increase by 3-13%. The favorability of collusion (both for almost all firms individually and for the cartel overall) is higher when the demand grows faster first then slows down, compared to slower first and then speeds up, as Figure 28 below illustrates.
Firm A
Firm B
Firm C
A+B+C

% Cashflow NPV improvement with collusion

slow-fast demand growth
fast-slow demand growth

decline-growth demand pattern
growth-decline demand pattern

Figure 28: Improvement in cash flow NPV for the major firms under collusion, for different demand growth patterns

The favorability of collusion to non-collaboration is not particularly affected by price elasticity, nor does the probability or magnitude of the demand perturbation seem to play a role in the incentive to collude.

In terms of the impact of supply structure on the desirability of cartels, the pattern that emerges from Section 4.4 is that, if the major firms dominate the market, there is a larger cash flow NPV to the major firms overall when forming a cartel and colluding on investment decisions to open fewer mines. This is true regardless of the relative cost and market share positions of the major firms relative to one another. In the base supply scenario of unequal market share and supply positions, Firm B and C, which have higher cost incentive mines and existing supply, benefit much more from the cartel than Firm A, which has more and cheaper existing and incentive supply.

4.6.2 Stability of Collusion and Partial Collusion

It is important to note that the cartel paradigm discussed in the cases above only illustrates the optimal policy only if all three firms were to collude. Besides the desirability of collusion based on firm and cartel NPV payoff, whether the three-firm cartel would be stable is another interesting question. Collusion policies where only one firm enjoys a higher NPV compared to the non-collaborative policy wherein two firms suffer a loss would not be attractive politically, even if the overall cartel NPV is raised. Collusion policies where all firms enjoy a higher NPV
are highly attractive politically. However, when forming a cartel benefits two out of the three firms, could the two firms collude and effectively force the third firm into the same decisions made under the cartel policy, even if it does not want to collaborate? Or would two of the firms have an incentive to form a cartel by themselves and exclude the third firm to earn greater cash flow NPV through decisions different from those that would be made under the three-firm cartel?

Unlike past literature which either has two players to simplify the game playing or identical multiple players (e.g. Murto et al., 2004), the non-homogenous three-player and realistic parameters of this model allows us to examine which of the major players might have more incentive to collude than others. In future work based on the market setup constructed in this thesis, the stability of the three-firm collusion and the motivation for only two of the firms to collude and exclude a third firm under different supply and demand conditions would be an interesting and fruitful direction of exploration.
Chapter 5 – Conclusion and Future Work

5.1 Conclusions

In the mining industry, one of the most central business planning decisions faced by firms is where, when, and by how much to expand their production capacity. In recent times, capital allocation is recognized as the top strategic risk for the industry (Deloitte & Touche, 2010). These investment decisions impact not only the market supply, price and the firms’ own profitability, but also the economics of the numerous manufacturing industries that rely on the commodities as raw materials. Appropriate investment planning methodology is both important to the mining industry and the wider economy.

Static DCF analysis is the standard approach for evaluating new mining projects in the industry. However, it has a number of important shortcomings, especially in the face of uncertainties in market conditions and for markets exhibiting imperfect competition where firms might influence price through their supply decisions. First, static DCF does not account adequately for the randomness of the cash flow variables. Second, static DCF ignores the value of waiting to start a project and managerial flexibilities in operating a project to maximize profit over time. Third, static DCF is only applied at the mine project level, which does not account for the impact of opening up a project on the firm’s existing mines through the effect of supply injection on price. Finally, in oligopolies, static DCF overlooks the strategic interactions between the major firms’ decisions.

To address some of these shortcomings and incorporate more complex dynamics into the DCF evaluation method, numerical methodological advances have been proposed by researchers, especially in the fields of real options valuation and real option games. However, to date, the literature has been largely been theoretical and based on highly stylized markets and firms with little resemblance to the real world. There have been very few comparative studies testing whether the more sophisticated DCF approaches help the firms realize better NPV outcomes than the simpler approaches.

The main objective of this thesis is to take steps towards filling this gap in literature and to evaluate the different mining investment decision methods of increasing scope and complexity in
the context of a market with realistic features. To this end, we construct three investment decision paradigms – positive-mine-NPV, positive-firm-NPV, and best-firm-NPV – optimize them as the firms would for an oligopolistic market that has three major firms and that has demand and supply parameters based on a real mineral market. Then, we run Monte Carlo simulations with these optimized investment policies to observe which paradigms generate superior realized NPV over an evaluation period of 27 years. The policy optimization and simulation is conducted for various market scenarios of different demand growth patterns, volatility, demand elasticity, and supply structure.

The same optimization and simulation tools also allow us to achieve a secondary thesis goal – to examine whether cartel-decision making by the major firms (as modeled by a fourth decision paradigm) could generate more attractive NPV for the firms and under what conditions such collusion is most attractive.

As the results and analysis chapter shows, in almost all scenarios, the game theoretic/option-based best-firm-NPV policy outperforms the positive-mine-NPV policy substantially for all firms, regardless their market and cost position. The former policy dictates the opening of fewer mines and at later times than the latter because the best-firm-NPV policy considers the negative price impact of opening new mines on the firms’ own profit and optimizes the opening time, while the latter opens mines on the positivity of the mine NPV alone. Surprisingly, the difference between the best-firm-NPV policy and the positive-firm-NPV policy is often small, suggesting that the consideration of mine opening from a firm level NPV perspective is more important to improving the NPV outcome for the firm than incorporating the optimization of mine opening timing or game theory. This result may be a consequence of having incorporated operational flexibility for all the methods, thereby taking into account the managerial flexibility portion of the value of the real options approach in the positive-firm-NPV investment method. Incorporating game theoretic considerations also does not seem to generate much improvement.

In the base scenario, the game theoretic/real options-based best-firm-NPV paradigm results in 35-38% higher cash flow NPV outcome for each of the three major firms over the baseline positive-mine-NPV paradigm. The simpler paradigm improvement of only incorporating the
profit impact consideration on the rest of the firm (i.e. the positive-firm-NPV paradigm) also results in 25%-27% higher cash flow NPV over the baseline positive-mine-NPV paradigm.

The scenario analysis of various demand parameter changes suggests that demand growth rate has a significant impact on the comparative performance of the investment paradigms. When demand grows faster, both the positive-firm-NPV and the best-firm-NPV paradigm outperform the simplest positive-mine-NPV paradigm by a wider margin than in the negative and zero growth scenarios. However, the gap between the best-firm-NPV and the positive-firm-NPV policies narrows, and even disappears under positive demand growth. These results suggest that, when demand grows, adopting the two firm-NPV based investment paradigms becomes more advantageous. However, the difference between the two improvement choices narrows. Assuming that demand grows at 1% annually, the pattern of demand growth has a more subtle impact on the relative performance of the paradigms. The best-firm-NPV policy seems to generate even more cash flow NPV benefit versus the base policy of positive-mine-NPV policy when the demand growth pattern is slow-fast and decline-growth rather than the opposite scenarios, but, as in the growth rate results, most of the gain seems to come from considering NPV on a firm level when making decisions. The relative performance of the different paradigms is not noticeably affected by changes in the demand perturbation magnitude or probability. As for demand elasticity, a more elastic demand makes the increases in NPV paradigm sophistication less valuable because of its negative dampening of the market quantity and price under the less expansionary policies, as well as its dampening of the negative price impact resulting from supply injection.

Supply structure variations produce harder to explain changes in the relative performance of the policies, because supply structure changes always impact not only the parameters we seek to vary (i.e. equal vs. unequal supply and cost positions, level of market concentration), but also inevitably the shape of the supply curve itself. More market concentration in the hands of the three major firms lead to a flattening of the supply curve and more lower-cost production volume, decreasing the incentive for incentive mines to enter under all paradigms, but affecting more heavily the more aggressively expansionary positive-mine-NPV paradigm. Consequently, the more sophisticated investment decision methods do not seem to improve the outcome of the decision as significantly when the market is more highly concentrated.
However, when we examine the NPV outcomes of greater versus lesser market concentration for a supply curve where the firms are identical, we do not observe the same results. Market concentration in this case does not change the favorability of the more sophisticated policies relative to the basic positive-mine-NPV policy. This contrast with the base scenario results from very specific differences in the cost positions of two of firm B and C’s mines. Hence, neither conclusion on the impact of market concentration is generalizable and the analysis must be performed for any specific market supply curve that we wish to examine.

Aside from changes in supply and demand parameters, changes in the order of decision-making, which are most relevant for the game theoretic paradigm, are also interesting to examine because they provide insight on first-mover advantage and relationship to cost position. We find that decision ordering produces significant but small (4%) differences in the NPV outcomes of the firms with no obvious first-mover advantage. However, one ordering, CBA, produces the best NPV outcome for all firms involved. When we eliminate the cost difference between the firms by making them identical, decision ordering becomes irrelevant because the firms all make the same decision in each period. However, when the market concentration of the three identical firms is increased so that the market no longer has the capacity to accommodate all three firms opening in any same period, the overall NPV still remains the same but the distribution to the three firms changes with decision ordering. There is a distinct disadvantage to being the last to make a decision in this equal supply with more concentration scenario.

In terms of the contribution of collusion decision-making to the firms’ realized NPV, collusion generally does produce superior NPV outcomes for at least two and often all three of the major firms compared to the non-collaborative best-firm-NPV approach. This suggests that cartel-based investment decision-making is favorable and politically feasible in this hypothetical market (absent regulatory constraints). There is especially significant payoff to collusion when demand growth is higher and when the pattern of growth is slow-fast or decline-growth. Volatility and elasticity of demand does not significantly affect the incentive to collude. There is also a larger payoff when the major firms occupy a higher share of the market.

Overall, the evaluation conducted in this thesis contributes another piece of the puzzle to the question of how useful having more sophisticated and hard to implement investment decision
methods might be. Firms are unlikely to incorporate better and more complicated investment planning approaches until solid evidence could be shown of their NPV-enhancing ability on realistic markets and firms.

5.2 Future Work

5.2.1 Game Theory Consideration in Choosing the Investment Decision Paradigm

The models in this thesis assume that all firms choose the same investment decision paradigm. In the real world, firms are free to choose their own investment method independently. In such mixed investment method market, there is no longer the knowledge by any one firm of what the others might choose as their investment paradigm. This situation gives rise to a more meta game theory question – how would firms choose their investment decision paradigm? And is there a dominant strategy for choosing one’s investment method? This is an interesting topic to investigate in future work.

5.2.2 Impact of the Threat of the Rest of the World Entering

Two important and closely related factors in determining price are the barriers to entry and the responsiveness of supply to changing demand (Darling, 2011). When the barriers to entry are high, the existing producers will enjoy more market power and influence over price. In this case, the barriers to entry are the price points that the third-party new supply require to enter the market. Future work should explore scenarios raising or lowering these barriers to entry, thereby examining how the different investment paradigms perform under different levels of barrier to entry to non-major firms, whose actions might well have a substantial impact en masse.

5.2.3 Accounting for Learning and Other Process Improvement Investments

In the current model, the sole determinant of longer term profit is the capacity decision of firms. Cost and capacity of the mines are considered exogenous and fixed. However, in the real world, both of these parameters could be improved through certain types of investments (e.g. knowledge generation, process improvement) (Dixit & Pindyck, 1995). These improvements could lead to greater cash flow improvements in the longer term than capacity expansion alone and could be included in future long-term investment planning models of even greater sophistication (Cavender, 1998).
5.2.4 Impact of Inaccurate Demand Forecasting

This thesis assumes that firms have an accurate forecast of future demand conditions in their expectations. Slater et al. (1998) argue that one of the key drawbacks of the DCF method is its bias when estimating the important parameters, such as future economic condition. One extension on the thesis could be to study the impact of the bias on the performance of the different methods. Per the recommendation in Bennion (1956), future work can analyze how far off a forecast could be before it leads to a bad decision with inferior NPV outcome. In future work, we can explore this metric as an additional way to evaluate the different investment decisions paradigms – the robustness of the methods to forecasting inaccuracies.
Chapter 6 – Appendix

6.1 Details of the Four Investment Paradigms

6.1.1 Positive-Mine-NPV Paradigm

The first investment paradigm modeled in this thesis – also the one commonly employed by firms, as the literature on actual firm practice mentioned in the previous section – is a firm deciding to open the mine with the largest NPV (if it’s also positive), calculated based on an expected future price path that results from averaging the results of several different potential market scenarios. In the model, the expected future price path is based on an arithmetic average of the prices resulting from three different potential scenarios: 1) the price staying the same in the future as the period of decision, which assumes that market capacity growth is in pace with demand growth; 2) if the opex + capex (amortized over the 27 years for NPV evaluation) for an incentive mine is exceeded by the price in a period, the mines will open. Since the mine opening in turn affects the price in the particular period, this process is run for 3 iterations or until the prices between iterations converge sufficiently, whichever comes first. 3) the same as scenario 2, but with the opening restriction for incentive mines lowered to opex being exceeded by the price.

In the model used for this project, the price paths are calculated by running the market clearing forward while assuming that other incentive mines that have not been opened would open when the price reaches a certain level. There are three different supply expansion scenarios considered: 1) no other new mine opening (a very optimistic scenario); 2) new mines opening when the price is above their opex (a pessimistic scenario); and 3) new mines opening when their incentive price is exceeded by the market price (i.e. their mine NPV, if the market price were to persist forever, would be non-negative after taking into account the initial capex). We take an average of the price paths resulting from the three scenarios to form the expected price path. The NPV of the mine is calculated based on the expected future price path, and the firm decides whether and which mine should be opened according to the highest positive NPV mine, if any.
6.1.2 Positive-Firm-NPV Paradigm

In the second mining investment decision method, the firm is more strategic about its mine opening decision and considers the price impact of the mine opening on the profitability of the rest of the mines in its portfolio. The firm would therefore only open the mine if the overall expected firm portfolio NPV, should the mine be opened, is larger than if the mine were not opened.

6.1.3 Best-Firm-NPV Paradigm

The third mining investment decision method is the most complex and sophisticated. It not only considers the firm-level NPV impact of opening up a new mine, but also how its competitors might react to its decision. In this decision method, the firm looks forward to all potential actions that the major firms could take and the states the market could be in, and then forms an optimal policy of mine opening that is contingent on the state of the world in order to maximize the future expected NPV at any given time. This decision method uses both the principles of game theory (in having each firm consider the optimal competitive response of its competitors) and real options (in recognizing the potential value in delaying mine openings and the flexibility of the mine that open to not operate if the price were to fall drastically). Since the competitive dynamics between the three firms center around decisions on quantity of production made in sequential moves, the “game” in this market is a variation of a classic Stackelberg game, and the optimal decisions of the firms in equilibrium is the subgame perfect Nash equilibrium – i.e. the strategy that maximizes each player’s interest, given the strategies of the other players. To solve for the Nash equilibrium policies, we use dynamic programming and backward induction, which are described in detail in the section on solving for the optimal policy.

6.1.4 Cartel Decision Paradigm

The cartel decision paradigm is distinct from the other paradigms in that it assumes a market in which the three major firms cooperate and maximize their joint benefit instead of individual benefit. As in the case of the best-firm-NPV policy, the “benefit” maximized is the firm-level NPV.
6.2 Specification of the Demand Function

The mathematical mechanism of the demand function used in this thesis is adopted from a previous paper on a similar topic (Murto et al., 2004). Following the paper's method, market demand is parameterized as a constant-price-elasticity demand function:

\[ P^t(Q^t, D^t, X^t, t) = a \times (X^t \times \frac{D^t}{D^0})^{1/\epsilon_l} \times (Q^t)^{-1/\epsilon_l} \]

where \( P^t \) is the price demanded, \( Q^t \) is the quantity demanded, \( D^t \) and \( D^0 \) are the underlying demand level at period \( t \) and period 0 respectively, and \( X^t \) is the demand perturbation factor. \( \epsilon_l \) represents the price elasticity of demand. The constant \( a \) is a calibration coefficient for the demand function calculated such that the period 0 supply curve and demand function would intersect at \( D^0 \), the market demand level for period 0.
6.3 Pseudocode of Key Models and Computation Modules

6.3.1 Market Supply-Demand Model

Description: given the states (mines opened), demand for the period, base demand, etc., calculate the market-clearing price and quantity\(^ {10} \), and the profit generated in this period for the different firms.

Update supply curve with the opened incentive mines.

Resort the supply curve by mine opex.

For each demand shock scenario

For each mine (starting with the lowest cost and going up)

Calculate \( q \), the cumulative supply lower than the cost of the current mine.

Calculate the price at the \( q \) on the demand curve (with the underlying demand known for the period).

If the opex at \( q \) is larger or equal to the price demanded OR if the opex at the next mine is larger than the price demanded (meaning that the cliff-face is crossed between this mine and the next), then this is the marginal mine and the market clearing price.

If the opex at \( q \) is larger or equal to the price demanded (i.e. NOT crossing the supply cliff face)

\(^ {10} \) When the demand curve crosses the stepwise supply curve on the vertical cliff-face between two mines, where it crosses determines the price and quantity, and the lower-costing mine is considered the marginal mine. The only exception is when it crosses at the opex of the higher-costing mine, in which case the higher-costing mine will be incentivized to produce as well and will be considered the marginal mine.
Market price is the operating cost of the current mine

Calculate market-clearing quantity (after adjusting for price elasticity) given the iso-elastic demand curve and the market price

\[ p = X^{(1/e)} \cdot a \cdot q^{(-1/e)} \cdot (D_0/D_t)^{(1/e)}; \]

else (i.e. the supply cliff face has been crossed)

Market price is \( p \), which is where the demand curve crosses the supply face

Market-clearing quantity is \( q \), which is where the demand curve crosses the supply face

Calculate the capacity utilization = market-clearing demand / \( q \)

Calculate the rewards for each player, if all mines operating are at the same capacity utilization

Do not go to the next mine on the cost curve

Else go to the next mine on the cost curve

Go to the next demand shock scenario

Return the market price, quantity, utilization, and diagnostics data
6.3.2 Calculation Optimal Policy under Different Paradigms

A. Best-Firm-NPV paradigm and cartel paradigm

Purpose: Find the market equilibrium optimal policy of mine openings that maximizes expected firm NPV for each firm (best-firm-NPV paradigm) and the policy that maximizes the expected NPV of the three major firms in total (cartel policy). For the best-firm-NPV paradigm, the market equilibrium optimal policy means that no firm would unilaterally change their policy to something else. There are potentially other non-equilibrium policies where all firms have better portfolio NPV than in the equilibrium, but which are not possible to reach in a game theory setting where the firms cannot collude.

For each decision period \( t = T \rightarrow 1 \)

Iterate over all the possible state variable combinations (whether each mine has been opened, whether demand has been impacted permanently in the past, whether non-major new incentive mines have opened)

For each state, iterate over all the possible mine expansion choices of the decision-making firm

Check if the mine is opened already. If yes, skip this choice. If not, open the mine and update supply curve

Update the state vector of incentive mines opened

If the decision period \( t \) is a price clearing period\(^\text{11}\)

Calculate the market clearing price and profit for all firms for 3 demand perturbation scenarios

If there was a mine opened, subtract capex from profit to calculate the reward in this period

---

\(^{11}\) Every year consists of 3 decision-making periods. Price clearing happens on period 3, 6, 9, and so on in order to allow all firms a chance to make a decision before the market price is determined and profit is calculated for each firm to minimize the profit impact of decision ordering.
Calculate the expected current rewards across the demand perturbation scenarios for all firms

Figure out what is the next state, given the action choice

Calculate the expected future rewards by looking up the value in the Value Matrix for period t+1 for the next state

Calculate the total expected value = expected current rewards + expected future rewards

Else if the decision period t is not a price clearing period

Find the total expected value based on the next state the present action would put the market in

Figure out which actions give the maximum firm NPV, and save the max value and best action into the value and optimal policy matrices for the best-firm-NPV paradigm

Figure out which actions give the maximum cartel NPV, and save the max value and best action into the value and optimal policy matrices for the cartel paradigm

Go to the next state combination

Go to decision period t-1
B. Positive-Firm-NPV paradigm: maximizing firm NPV without considering the competitive dynamic

Purpose: Makes decision and simulate the market under the positive-firm-NPV paradigm. The basic logic is:

- Go forward through all the time periods. If the expected cash flow NPV impact of opening up a new mine on the firm is positive, then it will be opened
- If there are multiple incentive mines fulfilling this criteria, open the one with the highest firm NPV
- Firms make decision sequentially (in order to be comparable with the other criteria, where decision has to be sequential)

For decision period $t = 1:T$

Determine which firm is to make expansion decision in this period

For each of the incentive mine of this firm that is not open already

Calculate the expected price (see next module’s pseudocode) if this mine were to be opened

Using the expected price path, calculate the expected firm-level NPV of opening this mine over the decision period of 27 years

If the mine has positive NPV impact on the firm, see if the NPV is the most positive (and if tied, the highest NPV/capex) out of the potential incentive mines to open for this firm so far.

If so, record this mine as the mine to open

Open the mine to open (i.e. highest NPV or NPV/capex mine that’s also NPV-positive, if any)

Record mine opening decision

Update the state vector of mines opened

If the decision period $t$ is also a price-clearing period

Let the demand perturbation be realized according to the probabilities
Calculate the market clearing price and quantities in this period; record them.

Record any permanent shift to the demand according to the price.

For each firm, record overall firm cash flow NPV from t=1 up to this period.

Go to the next decision period t+1.
C. Positive-Mine-NPV paradigm: expansion when the incentive mine NPV is positive

Purpose: Makes decision and simulate the market under the positive-mine-NPV paradigm. The basic logic is:

- Go forward through all the time periods. If the expected NPV of a new mine is positive, then it will be opened
- If there are multiple incentive mines fulfilling this criteria, open the one with the highest NPV
- Firms make decision sequentially (in order to be comparable with the other criteria, where decision has to be sequential)

For decision period $t = 1:T$

Determine which firm is to make expansion decision in this period

For each of the incentive mine of this firm that is not open already

   Calculate the expected price (see next module’s pseudocode) if this mine were to be opened

   Using the expected price path, calculate the expected NPV of opening this mine over the decision period of 27 years

   If the mine is NPV positive, see if the NPV is the most positive (and if tied, the highest NPV/capex) out of the potential incentive mines to open for this firm so far.

   If so, record this mine as the mine to open

Open the mine to open (i.e. highest NPV or NPV/capex mine that’s also NPV-positive, if any)

Record mine opening decision

Update the state vector of mines opened

If the decision period $t$ is also a price-clearing period

   Let the demand perturbation be realized according to the probabilities

   Calculate the market clearing price and quantities in this period; record them
Record any permanent shift to the demand according to the price

For each firm, record overall firm cash flow NPV from \( t=1 \) up to this period

Go to the next decision period \( t+1 \)

D. Expected price calculation\(^{12}\)

*Purpose: calculate the expected price path, which is used in decision-making under the positive-mine-NPV and positive-firm-NPV paradigms.*

For period \( =t : T \), figure out what is the price path in a market that obeys each of the 3 rules below:

- **Rule 1:** No price change from now (this assumes market capacity growth is in pace with demand growth)
- **Rule 2:** Other mines not already open come on if the opex is lower than expected price in the current period, and the lowest opex mine comes on first
- **Rule 3:** Other mines not already open come on if the opex + capex amortized over 25 years is lower than the expected price, and the lowest opex+amortized capex mine comes on first

Take a weighted average of the 3 price paths produced by different rules for incentive mines to start (default is equal weight)

\(^{12}\) Note: For each rule in each period, we calculate the expected price in each period (weighted average over the 3 different demand fluctuations). Also, for rule 2 and 3, we assume perfect price foresight by the firm. Hence, we first determine mine opening based on an expected price path (in this case, I used the flat price from rule 1). Then, we iterate, using the outcome price path as the expected price path, until convergence of the two within 2 dollars on average or after 3 iterations.
6.3.3 Market Simulation Module

Purpose: Simulate the market with stochastic demand perturbation. Used for paradigms that need to be optimized first to produce the optimal policy matrix (best-firm-NPV policy and cartel policy)

Set the number of simulation, the order of the firms in decision-making, and the size of the demand perturbation

For each simulation run

- Set base state vector (no incentive mines open yet)

For decision period \( t = 1 \) to \( T \)

- If it’s this firm’s turn to act (according to a predetermined fixed decision order)
  - Look up the optimal action (based on the states and time period) from the optimal policy matrix calculated in the previous sections
  - Update the state vector with the optimal action
  - If the optimal action included opening a mine
    - look up the mine’s capex and remember it
    - record the time period in which this mine has opened for output

- If the period \( t \) is a price clearing period
  - simulate the demand perturbation to get the post-perturbation underlying demand for the period
  - call the market clearing function to figure out price and quantity for each firm
  - save the market price, quantity, utilization rate, and diagnostics
figure out if any permanent demand shift or entrance by non-major new supply has happened due to the price
save for each firm its current time period reward, total value so far, and quantity produced
update the states for the next decision period
if the period t is not a price clearing period
update the states for the next decision period
go to the next decision period
go to the next simulation run
### 6.4 List of Demand Scenarios and Their Description

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base</strong></td>
<td>1% annual growth</td>
<td>Growth that will result in a final amount in the steep portion of the supply curve</td>
</tr>
<tr>
<td></td>
<td>(29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Scenarios for growth rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Super-fast</strong></td>
<td>2% annual growth</td>
<td>The super-fast, faster and slower scenarios offer insight into how different pace of demand expansion in a market might affect the desirability of using one investment paradigm versus another</td>
</tr>
<tr>
<td></td>
<td>(67.3% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Faster</strong></td>
<td>1.5% annual growth</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(47.3% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Slower</strong></td>
<td>0.5% annual growth</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(13.8% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Flat</strong></td>
<td>0% annual growth</td>
<td>Mature market with no technology transformation – hence underlying demand is constant</td>
</tr>
<tr>
<td><strong>Shrinkage</strong></td>
<td>-0.5% annual growth</td>
<td>Market that is shrinking as a result of structural economy shift, technology change away from the raw material, etc</td>
</tr>
<tr>
<td></td>
<td>(-12.2% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Scenarios for growth pattern</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slow-fast</strong></td>
<td>0.5% for first half, 1.5% for second half</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Fast-slow</strong></td>
<td>1.5% for first half, 0.5% for second half</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Fast-flat</strong></td>
<td>2.01% for first half, 0% for second half</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td><strong>Fast-slow-fast</strong></td>
<td>1.266% for first and final third, 0.5% for second third</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td>Growth Pattern</td>
<td>First Half Growth (%)</td>
<td>Second Half Growth (%)</td>
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<tr>
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</tr>
<tr>
<td>Slow-fast-slow (S-shaped)</td>
<td>0.5% for first and final third, 1.951% for second third (29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td>Growth-decline</td>
<td>2.523% for first half, -0.5% for second half (29.5% total growth)</td>
<td></td>
</tr>
<tr>
<td>Decline-growth</td>
<td>-0.5% for first half, 2.523% for second half (29.5% total growth)</td>
<td></td>
</tr>
</tbody>
</table>

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Bibliography


Knights, R. (2013). *Why the predicted iron ore glut is no certainty.*


Slade, M. E. (2000). Valuing Managerial Flexibility:


