Adding Value to a Mining Corporation through Project Portfolio Management: Combined Approaches of Portfolio Theory and Multi-Attribute Utility Theory

Carolina Yessenia Campos Valverde

Department of Mining and Materials Engineering
McGill University, Montreal, Quebec
March 2023

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of **Master of Science**

Abstract

A mining corporation has the potential to extract additional value through management strategies, for example, project portfolio management. In mining, project portfolio management can be interpreted in two forms for a large mining corporation listed on the stock market: (1) the company receives project proposals from its mines (e.g., expansion, equipment replacement, social, and new exploration projects); or (2) the project transitions from one stage to another (e.g., licensing to exploration, exploration to development, development to operation, and operation to closure). The problem is determining which project should be supported to maximize utility (e.g., profit maximization, environmental compliance, social acceptance, and/or increasing resources) while minimizing risks.

This thesis applies three approaches to solve project selection: (1) Markowitz Theory, (2) Kataoka's Criterion, and (3) the utility additive method. The performance and applicability of these approaches are demonstrated through case studies, and the advantages and disadvantages of each approach are identified.

Résumé

Une société minière a le potentiel d'extraire de la valeur supplémentaire grâce à des stratégies de gestion, par exemple, la gestion de portefeuille de projets. Dans le secteur minier, la gestion de portefeuille de projets peut être interprétée sous deux formes pour une grande société minière cotée en bourse : (1) la société reçoit des propositions de projets de ses mines (par exemple, expansion, remplacement d'équipement, projets sociaux et nouveaux projets d'exploration) ; ou (2) le projet passe d'une étape à une autre (par exemple, de l'autorisation à l'exploration, de l'exploration au développement, du développement à l'exploitation et de l'exploitation à la fermeture). Le problème est de déterminer quel projet doit être soutenu pour maximiser l'utilité (par exemple, la maximisation du profit, la conformité environnementale, l'acceptation sociale et/ou l'augmentation des ressources) tout en minimisant les risques.

Cette thèse applique trois approches pour résoudre la sélection de projets : (1) la théorie de Markowitz, (2) le critère de Kataoka et (3) la méthode additive d'utilité. La performance et l'applicabilité de ces approches sont démontrées à travers des études de cas, et les avantages et les inconvénients de chaque approche sont identifiés.

Acknowledgments

First, I would like to thank my supervisor, Professor Mustafa Kumral, for his support and guidance in my studies these past two years and express my gratitude to the Peruvian Institute of Mining Engineers, which sponsored my studies at McGill University.

I am pleased to have been part of the Mineral Economics Laboratory, where I shared space with colleagues from different cultures and backgrounds, which allowed me to grow up not just academically but personally. In particular, I would like to thank my dear friend Sena Senses for her advice on my research and for her high-quality friendship. Also, I would like to thank my friends, Zhely, Kathy, Christian, and Brian, for being part of my journey these last five years. And Thomas, my sweetheart, for always being at my side cheering me. Finally, and most significantly, my extremely thanks to Silvia, Arnulfo, Jean, Tephy, Lety, and Leandro, my adorable family, for their unconditional love and the innumerable lessons I have received from them in my life. They inspire me, make me laugh, and help me remember what is essential in life.

Contents

List of Figures

List of Tables

List of Abbreviations

PM	Portfolio management
PPM	Project portfolio management
MCDM	Multi-criteria decision-making
UTA	Utility additive method
LP	Linear Programming
QP	Quadratic Programming
ESG	Environmental, social, and (corporate) governance

1. Introduction

1.1. Problem Statement

A portfolio is a set of investments, including stocks, buildings, bonds, cash, and intangible assets. Its purpose is to maximize return and minimize risk for an investor. By comparison, project portfolio management (PPM) refers to the group of projects held by an organization to achieve its goals. These projects could be in many forms, such as new investment, capacity expansion/reduction, new procurement strategies, increasing environmental compliance, or social acceptance projects. The PPM set includes project analysis, selection, prioritization, and supervision activities (Enoch, 2019).

An international mining corporation can be organized into units or divisions based on the continent where mines are operated, commodity type, or size of operation (e.g., Australian operations, gold operations, or medium-size operations). Divisions are subject to:

a. Legal frameworks of the countries where they operate

b. Unique geological and rock characteristics of each operation

c. Specific environmental and social sensitivities.

Central management evaluates the performance of each division based on whether targets are accomplished, for example, production rates, environmental compliance, safety performance requirements, and the level of acceptance of operation by communities. Every year, each division proposes various projects based on the corporation’s strategy. Central management collects these proposals.

Under budget constraints, some of the proposed projects are supported after consideration of several parameters: the required capital, the past performance of the division, project length, corporation priorities (e.g., the increased efficiency and performance, exploration projects, increased environmental compliance, resolving social licenses issues, and continuous improvement), the risk associated with each project, and decision timing.

The evaluation of mining projects has become more complex due to the growing number of government regulations, the need to find and exploit more remote and deep deposits, and various social and environmental restraints. Even though mining corporations are profit oriented, safety, environmental, and social acceptance are the utmost criteria that must be met. As environmental sustainability commitments and social issues become stricter and more pressing, mining corporations emphasize their portfolio strategies to be more effective and aligned with contemporary and future challenges. The threat of climate change is a significant priority for mining operations, as is the need to transition to clean energy. PPM should address these concerns to support mining projects (Lindsay Delevingne, 2020).

PPM is not a widely studied topic in the mining industry. Mining corporations have a history of applying strategies based on the expertise and judgement of decision-makers. These strategies are commonly criteria decisions based on scores to rank projects and prioritize tasks. However, since technology has allowed more projects to be under consideration, new strategies to build up a portfolio in mining corporations are required. Therefore, the problem statement of this thesis is: *How do mining corporations allocate limited resources to decide which projects to support within a portfolio so that utility is maximized?*

The Enterprise Portfolio Management Council (2009) raises five crucial questions to achieve a prosperous PPM considering the corporation’s strategy (Figure 1-1). The answers to these questions will direct an organization toward successful PPM.

Figure 1-1 Five crucial questions for successful project portfolio management (adapted from The Enterprise Portfolio Management Council, 2009)

The research presented here identifies three approaches to investment PM and determines which one of three models best dovetails with the direction of a project portfolio in the mining industry: (1) Markowitz Theory, (2) Kataoka’s Criterion, and (3) the utility additive method (UTA).

1.2. Research Objectives

1. Analyze the value-adding potential of PPM for mining corporations.
2. Propose project portfolio management approaches that can be used in the minerals industry.
3. Demonstrate the effectiveness and applicability of the proposed techniques through case studies.

1.3. Economic and Environmental Benefits

PM is a critical factor affecting the success of an organization. As mining methods, evaluation criteria, mining finance, explorations techniques, and innovations have diversified, the types and contents of proposed projects have significantly increased.

The principal economic benefit of this work is to provide information to aid decision-makers in choosing the most worthwhile projects to be developed, considering the risks inherent in mining projects. Also, this research attempts to demonstrate the importance of an improved decision-making process in selecting projects under the ongoing pressure to reducing carbon emissions and corporate commitments to contribute to the fight against climate change.

1.4. Originality of Contribution

The originality of this study relies on proposing models to select projects within a portfolio of a mining corporation, considering parameters and risks that are unique to the mining industry, such as uncertain commodities price and social, environmental, and political risks. The project selection problem is not well studied in mining academia. Furthermore, this research analyses how these uncertainties affect the portfolio and the outcome. Having more tools and strategies to develop a portfolio will improve a corporation's performance.

1.5. Thesis Organization

The present thesis is organized as follows:

- **CHAPTER 1** describes the problem statement, research objectives, and economic benefits.
- **CHAPTER 2** reviews the concepts of investment PM and project PM in extractive industries, mining business models, and multi-criteria decision-making (MCDM) tools.
- **CHAPTER 3** describes the methodologies proposed to apply in the construction of project portfolio in the mining industry.
- **CHAPTER 4** develops Makowitz and Kataoka's models to optimize the sale strategy of a mining corporation.
- **CHAPTER 5** applies the Makowitz and Kataoka's models to select the most profitable projects in a multi-division portfolio of a mining corporation.
- **CHAPTER 6** explores the use of the UTA to select projects by a worldwide mining corporation.
- **CHAPTER 7** concludes the thesis, summarizes the benefits of the methodologies developed, and suggests future work.

2. Literature Review

This chapter introduces concepts related to investment and project portfolio management and reviews previous work in extractive mineral industries. First, the features and current challenges of the mining business are introduced, and a comprehensive review on the literature is provided. Then, the various ways PPM helps mining companies to solve some of their current challenges are discussed. Finally, MCDM and its application to PPM are given.

2.1. Mining Business Challenges

The mining business requires significant investment to develop the projects. Therefore, comprehensive financial analysis and decision-making processes are needed. A mining operation involves a multitude of activities, including engineering, environmental protection, procurement, maintenance, and community acceptance. The management of this complex system needs careful strategies to sustain operations. This is more challenging for international mining corporations that govern mines which are diversified in terms of geography and commodity types. Given that mining is a risky business, risk management is an additional factor determining projects.

A mining corporation's business model should consider a mine-to-market value chain consisting of activities from the extraction of the materials to the supply of the final products to clients, depending on two principal features (Figure *2-1*): interconnected activities and assets. Activities are focused on delivery of the final product to the clients, who may be located in other countries or continents and need to meet the specifications of final product. Because of the inherent complexity of mining value chains, all assets, such as mining equipment, processing plant, and port transportation must be available at an acceptable level. Managing the value chain system transparently can help businesses create value and be more competitive in the market since it provides flexibility, which is necessary to adapt required changes in business models (Görner, 2020).

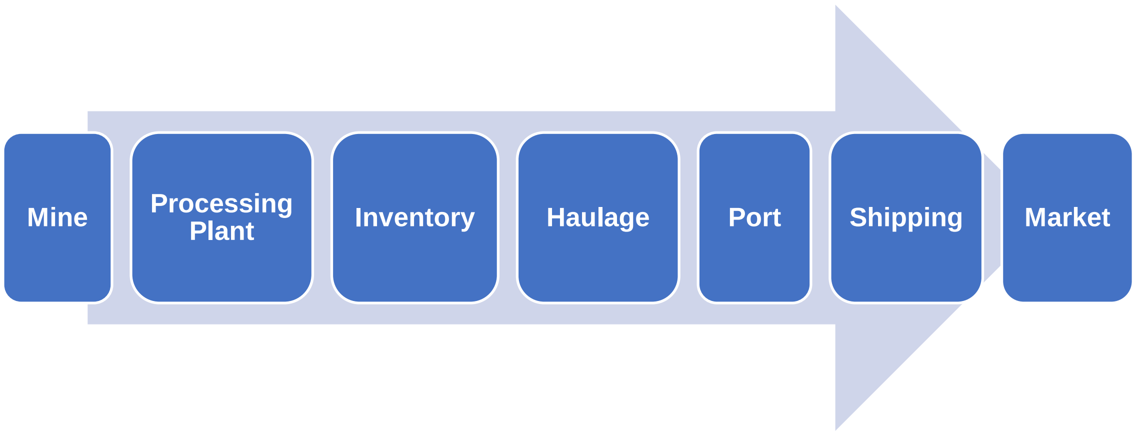


Figure 2-1 Mine to market value chain (adapted from Görner, 2020)

Another significant aspect of mining corporations is holding assets with the following features:

- Varied geographic locations
- Diverse commodities
- Project stage (scope, pre-feasibility, feasibility, and ongoing projects)
- Investments with varying ownership rates (joint ventures)

Consequently, corporations tend to structure their business by grouping assets with similar features (e.g., Figure *2-2*). While small companies can opt for a hierarchical organization model, transnational corporations and multiple metals have divided the management of the business by country, continent, material(s) produced, or group(s) of materials produced. For instead, Rio Tinto® structures its business into four commodities and a commercial group. Similarly, Teck Resources Limited® is divided into three principal divisions and energy assets. On the other hand, BHP Group Ltd® delimits its business into Minerals Australia and Minerals Americas, adding two groups for petroleum and commercial assets. Vale® structures its organization into iron solutions, energy transition materials, and other assets. Glencore® divides its business into industrial and marketing departments.

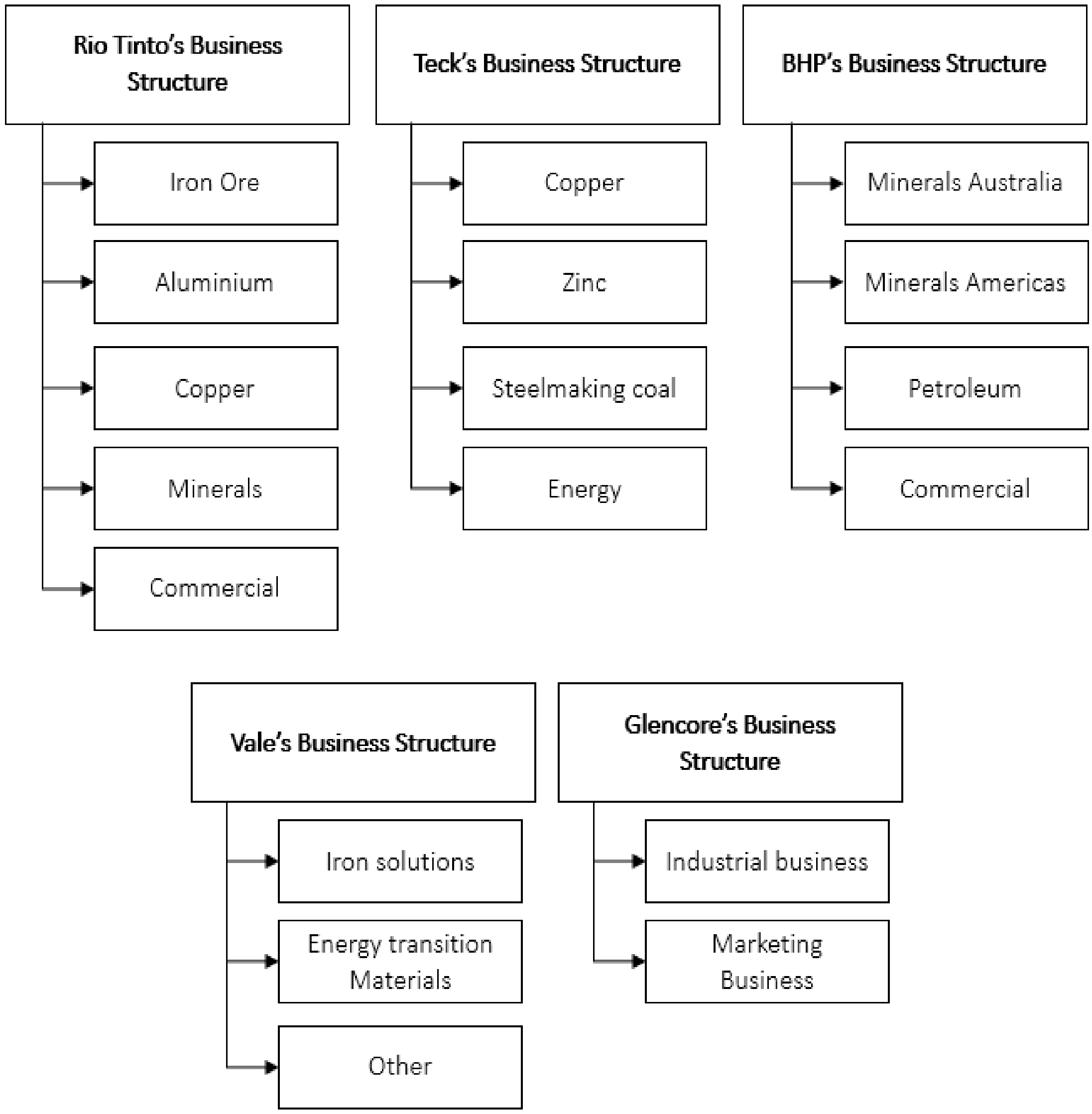


Figure 2-2 Examples of mining company business structures

Recent studies have focused on identifying the best structure for a mining corporation. Yaschenko, Polyakov, and Sabitova (2021) highlighted the substantial capital investments required in the mining business and how effective management is relevant to succeed financially. They studied the organizational structure of six large-scale potash producing companies and identified the criteria used to divide the organizational units, concluding that in the future, there will likely be a decrease in the number of management levels, with lower levels having more responsibility in decision-making within their tier. Considering business model and organizational structuring difficulties, three principal risks are implied in the success of mining business: commodity price risk, country risk, and credibility risk.

The commodity price risk is a form of financial risk related to the profitability and performance of an entity, depending on commodity price variability. Commodity prices are controlled by external market forces and macro-economic dynamics such as demand, foreign currency fluctuations, and interest and exchange rates. They affect not only product pricing, but also production costs and access to credit (Deloitte, 2018).

Country risk is associated with the economic outlook of the county in which an international mining corporation plans to develop a mine. It mainly results from political instability and corruption in underdeveloped countries, resource nationalism concerns, and environmental and social aspects gaining attention in countries whose economies lie in mining operation (Renaud & Kumral, 2021). Furthermore, given that risk related to social context is significant, integrating social and cultural issues in the early stage of project evaluation is critical because the capital project is presented during the later stages of long-term studies, development, construction, operation, and closure (Smith & Brooks, (2018).

The third principal risk, credibility risk, has a strong relationship with the potential of companies to attract investors and raise their capital. Corporate social responsibility, environmental consciousness, and ethical behavior determine a mining corporation's reputation. The Environmental, Social, and Governance report requires organizations to become more transparent concerning financial parameters and relieves risks that can damage the corporation's reputation. The environmental element refers mainly to the business's carbon footprint. The social factor encompasses inclusion programs, gender and racial diversity, and the impact on the community. The term governance evaluates how directors manage changes and interactions with shareholders (Bissoondoyal-Bheenick, Brooks, & Xuan Do, 2023).

In addition to the complication of the organizational structure and risks, public mining companies must also consider capital market dynamics. Mining corporations listing in stock exchange are classified as senior and junior. Senior corporations have significant capital, a long history, and are well known to investors. Junior corporations consist of small or new companies with limited capital, who are looking for investors to grow. The Toronto Stock Exchange (TSX) and Toronto Stock Exchange Venture (TSXV) are among the largest stock exchanges through which mining projects are financed. The former is the home of senior corporations, and the latter is the home of junior corporations. More than 1,000 corporations are listed in both stock exchanges.

Mining companies are more complicated than other commercial businesses and should have a holistic view of the market to manage their firms effectively. Mining corporations such as BHP (2021), Teck (2022), and Rio Tinto (2022) credit the success of their business to two critical aspects: a well-diversified portfolio and exemplary performance in their operations. A third factor is the current global situation, which demands that mining companies begin to focus on those commodities necessary for a responsible future, such as rare earth elements and other critical materials for clean energy production and storage. Given the shift towards a more sustainable industry, mining companies must establish an innovation strategy within their culture to stay competitive and avoid potential adverse consequences (Balci & Kumral, 2022). In addition, innovation can generate more value if new business models and stronger community and government relationships are established.

A well-rounded business strategy should include all aspects/drivers of a mining corporation. However, innovativeness is difficult for mining operations due to high exploration costs, mining-related risks, and the long lag time between discovery and profitable operations. Project PM presents a potential strategy for innovation because allocating resources efficiently brings strategic value to mining operations.

2.2. Investment Portfolio Management

This section reviews how PM is implemented in the investment field. Here, the term "investment PM" is introduced and explained related to the stock markets. The principal activities of investment PM are meeting targets, establishing asset allocations, regulating investment policy statements, balancing risk, and supervising performance (Figure *2-3*; Casterline & Yetman Jr., 2010).

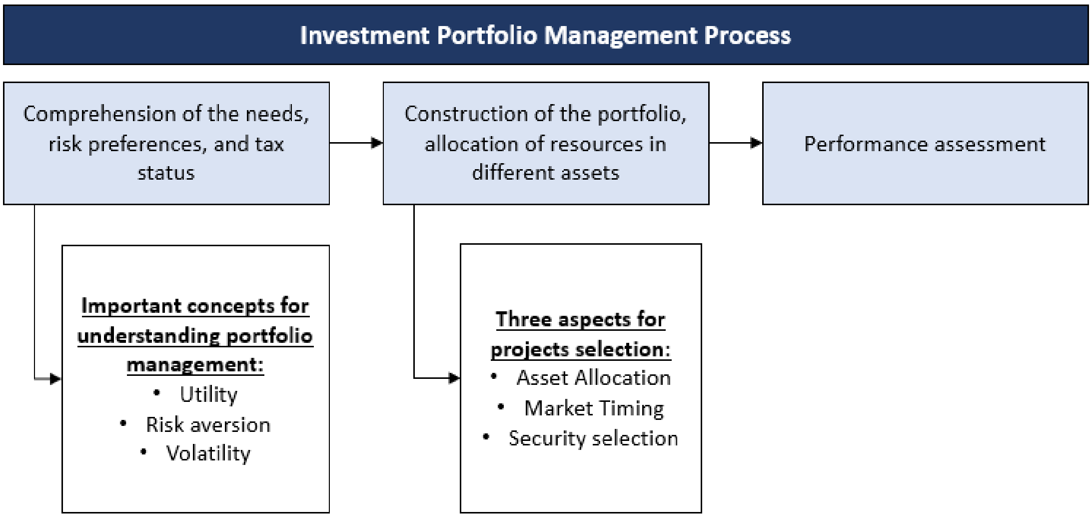


Figure 2-3 Investment portfolio management process

The first stage of investment PM involves the comprehension of three parameters: utility, risk aversion, and volatility. Utility assesses the satisfaction when a product or service is consumed. The benefits of a product will be represented with a positive utility, and the objective of a higher satisfaction will consider maximizing the utility. Risk aversion or risk tolerance constitutes the trend of an investor to avoid risk, which will increase with the prediction of obtaining a higher benefit. Volatility is a measure of the data uncertainty; it used to be represented by the standard deviation (Cernauskas, 2011).

The second stage of investment PM is resource allocation, which comprises three crucial aspects: asset allocation, market timing, and security selection. Asset allocation is the activity of including different kinds of assets in the portfolio, allowing the investor to diversify his portfolio and taking into consideration the two main features of each asset: the expected return and the risk to be assumed. As a result of this activity, the investor estimates the prosperity or failure of the portfolio. Market timing is related to an investor's ability to make predictions about how the market will play and react by quickly modifying his portfolio, aiming to add value to it. The modifications are new strategies that the individual proposes based on his criteria. Security selection comes after the asset allocation activity has been finalized and refers to the act of choosing specific securities from the categories of assets already selected, all with the intention of having a well-defined portfolio (Swensen, 2000).

The third stage of investment PM, performance assessment, can broadly be defined as the analysis, evaluation, presentation, and magnitude of investment outcomes. Performance assessment focuses on producing information about the return and risk during a specific period, allowing the managers to take corrective actions to improve the portfolio (Illmer & Senik, 2013).

The original portfolio selection problem can be represented mathematically as the maximization of the return (Equation 2.1), where x_i is the decision variable that represents the percentage of the investment to put into asset i and r_i represents the expected return rate of asset i.

$$\sum_{i=1}^{n} r_i x_i \tag{2.1}$$

Equation 2.2 notes that the objective function is subject to the assumption that all the capital should be invested.

$$\sum_{i=1}^{n} x_i = 1 \quad x_i \geq 0, i = 1,2,3,..,n \tag{2.2}$$

Several studies have aimed to optimize investment portfolio development. Modern portfolio theory, led by Markowitz, has two objectives: minimize the risk and maximize the level of return expected. The Markowitz model uses a mean-variance-covariance matrix to measure risk. It seeks a trade-off between risk and expected value from allocating resources (Steuer & Na, 2003).

The application of utility functions has also been studied to manage investment portfolios. Considering long-term investments and different periods, Warren (2019) emphasized that the mean-variance model considers one period and not the investors' priorities and goals. Moreover, he found that optimizations based on utility functions are better at adapting the preferences and objectives of the investor, creating more effective portfolios.

2.3. Project Portfolio Management

PPM is an essential activity for a business, which operates on strategic and the tactical levels (Edgett, 2010). Similar to PM, the objective of PPM is to achieve an organization's strategic goals (

Figure *2-4*). A PPM manager focuses on detecting, prioritizing, selecting, managing, improving, and supervising the most efficient projects: they have the authority to select, prioritize, deprioritize, accelerate, or delete projects from their list (Cooper, Edgett, & Kleinschmidt, 2001).

Figure 2-4 Portfolio management structure and its interdependency with the other concepts (adapted from Cooper, Edgett, & Kleinschmidt, 2001)

The PPM process has three standardized phases: planning, authorizing, and monitoring and controlling. Each stage has a defined timeframe (one year, one semester, or one quarter) to which it must adhere to achieve the business's success. The timeframe estimation will depend on portfolio complexity and magnitude. The Project Management Institute defines nine standard stages, which expand the three phases above (Figure 2-5):

1. Planning
    a) Identification of current, new, and potential components in the portfolio.
    b) Categorizing of projects with the same evaluation process and shared goals.
    c) Evaluation of all information to help the board produce recommendations.
    d) Project selection is a decision based on output from the evaluation stage.
    e) Prioritization, listing the most important to less important project to execute.
    f) Portfolio balancing supports the corporate strategic vision by having diverse projects.
2. Authorization aims to set the criteria by which the portfolio will be assessed and to allocate the financial resources.
3. Monitoring and controlling, encompasses constantly reporting, reviewing, and making changes to align the portfolio with corporation objectives.
4. Strategic change as needed to achieve the initial objectives.

Throughout this process, the PPM team is responsible for reviewing and adapting each stage, depending on the portfolio needs (Mathur, 2006).

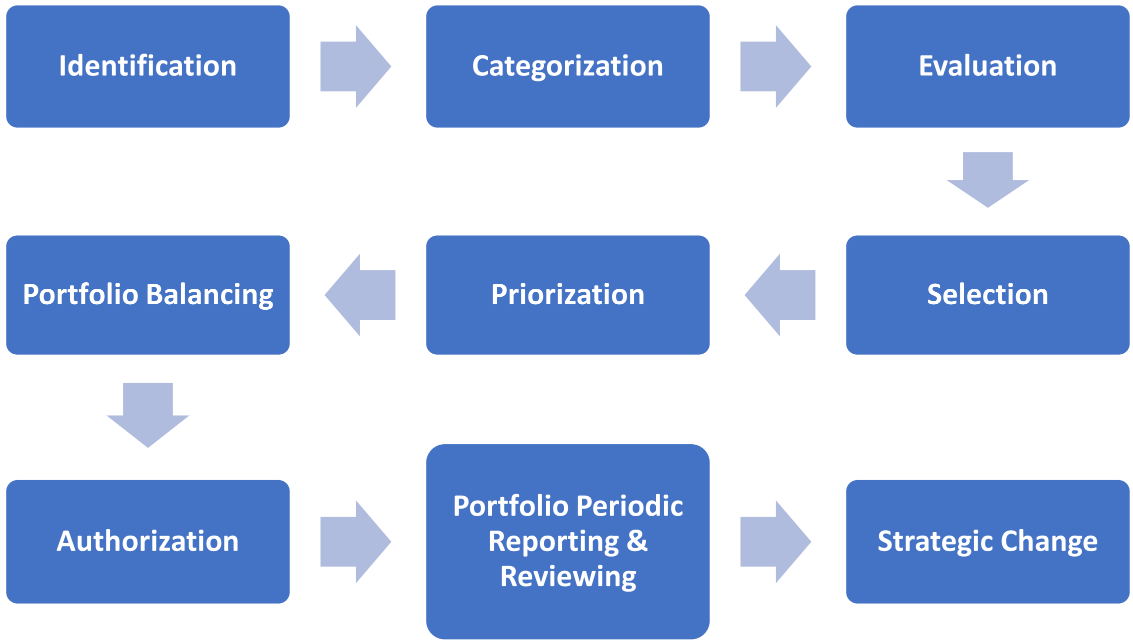


Figure 2-5 Project portfolio management processes (adapted from Mathur, 2006)

According to Edgett (2010), four principal challenges are faced in PPM. First, new projects must predict with forthcoming events based on uncertain and unreliable information. Second, managing the portfolio is a dynamic business; new data might change the position of the project. The third challenge is related to the difference in the stages of the projects competing for funding; projects contrast in quantity and quality of information. Finally, a well-known problem is the limited available resources.

Meskendahl (2010) proposed a conceptual model to bridge the initial strategy, project portfolio selection, PM, and achievement of business objectives. The model highlights the importance of strategic orientation in project selection and the relevance of the strategy in the long-term outcomes of the business.

Companies use internal and external aspects, the marketplace, and the character of the business to establish the central strategy, which in turn specifies the objectives of the portfolio and, simultaneously, the resources required to accomplish the goals (Figure 2-6; Archer & Ghasemzadeh, 1999). When the strategies are related to innovation, integrating a portfolio approach is essential to establishing effective inter-organizational collaboration. Organizations involved in inter-organizational activities are more likely to succeed in their innovative strategies, such as creating a new product or including innovative approaches to improve an existing product (Dries Faems, 2005).

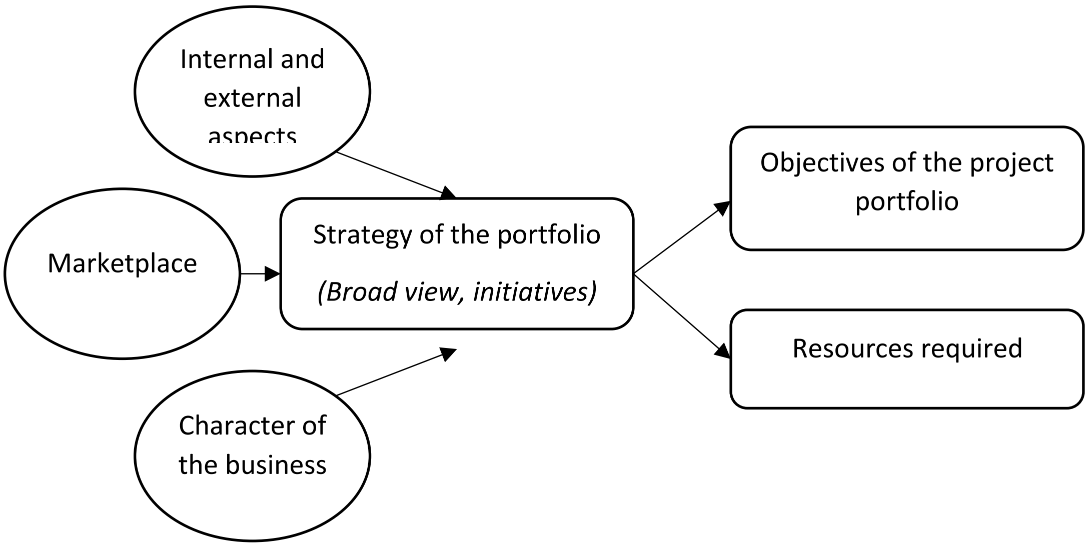


Figure 2-6 Portfolio strategy process: inputs and outputs

2.4. Portfolio Management and Project Portfolio Management in Extractive Industries

Previous studies on PM and PPM in extractive industries have been undertaken from two perspectives: that of investors to choose the most profitable companies to invest their capital (PM) and that of the corporation board to select the ideal projects to develop (PPM). It is interesting to note that the two perspectives have a strong relationship, as optimizing the PPM of companies will add value to the shareholders.

From an investor's perspective in the oil and gas industry, Qin, Zhen, Sijin, and Dong (2014) proposed a portfolio optimization model to select projects from a capital budgeting viewpoint. The authors used portfolio theory to analyze how to balance return and manage risk, introducing the "operational premium" to enhance the portfolio. The operational premium—the value added by oil executives in comparison with ordinary stock investors—is related to the ownership interest and operating efficiency. The study showed that oil and petroleum executives have technical skills that allow them to generate a higher operational premium. Nineteen project simulations with different degrees of operational premium showed that the expected return increased and the risk decreased when the corporation had more control over its assets. Higher risk tolerance could improve the portfolio's utility (Qin et al., 2014).

Gama and Teixeira (2015) proposed a multi-attribute utility function to select exploration and production projects in the development stage. They describe three synergies between projects that should be evaluated in the petroleum and oil industry. 1) Fiscal synergy refers to the terms of contracts between the petroleum industry and the government. Capital investment can be reduced is two projects share the same contract. 2) Project design synergy describes the advantages that may result from developing two projects with common facilities, infrastructure, and logistic requirements, among others. 3) Information synergy is the opportunity to have additional information if projects have similar backgrounds. The study shown the importance of quantifying the synergies in portfolio development based on the unit's performance and the importance of a preference set considered for the decision maker. Also, the authors highlight that decision-makers should be knowledgeable about the procedure of the multi-attribute utility theory to have efficacy in the model.

Furthermore, Ramírez-Orellana, Martínez-Victoria, García-Amate, and Rojo-Ramírez (2023) investigate the impact of sustainability assessment in the oil and gas industry to grow their market capitalization and attract investors. The study found that adopting environmental, social, and governance practices in the oil and gas sector improves investor portfolio performance.

Similar to the oil and gas industry, mining needs tools to select projects. Smith, Pearson-Taylor, Anderson, and Marsh (2007) were the first to link project valuation, capital investment, and strategic alignment in a mining corporation. To align the investment decision with strategic objectives, they found that a structured planning process is needed, and the application of discounted cash flows should be combined with other factors. Moreover, implementing technical tools to improve data and carry out evaluations will allow mining corporations to enhance the quality of the decision-making process and develop projects effectively.

Seeger (2019) performed multiple scenarios over the stages of mining operations to guide mining operations looking for investors, investors searching to capitalize in the mining sector, and governments planning to grow their mining sector. Njike and Kumral (2019) proposed a model for allocating resources in mining corporations based on operational performance. The method applies the Markowitz mean-variance theory to minimize risks and achieve the expected return defined in the portfolio. They found that diversifying the portfolio increases the net present value, and moderately the projects correlated will decrease the risk; Further, the number of projects approved increases if the performance of the projects as a whole increases (Njike & Kumral, 2019).

2.5. Multi-criteria Decision-making

In their comprehensive review of 265 publications on MCDM applications in finance, Steuer and Na (2003) criticized the bi-objective optimization of maximizing return and minimizing risk, arguing that because multiple objectives are faced in a portfolio problem, multi-criteria tools in finance become more relevant. MCDM can tackle complex decision problems where more than one factor should be considered (Doumpos & Zopounidis, 2004). MCDM assists in making decisions at the strategic change stage. Strategic decisions are made by top directors in the business and can seriously affect the organization. Because decision-makers deal with uncertainty, precise prediction of future results becomes a problematic activity (Montibeller & Franco, 2010). Thus, MCDM should be included in the early stage when organizations shape their vision and strategic objectives.

Various MCDM methods can be used to address four problems, depending on the decision-maker's viewpoint (Table *2-1*). 1) The choice problem aims to select the most convenient option or a small group of options. 2) The sorting problem classifies the options into predefined categories. 3) The ranking problem lists the options from the best to worst. 4) The description problem describes the options and their implications.

Table 2-1 multi-criteria decision-making methods for four problems (from Ozcer, 2021)

Choice	Ranking	Sorting	Description
AHP	AHP	AHPSort	
ANP	ANP		
MAUT/UTA	MAUT/UTA	UTADIS	
MACBETH	MACBETH		
PROMETHEE	PROMETHEE	FlowSort	GAIA, FS-Gaia
ELECTRE I	ELECTRE I	ELECTRE-Tri	
TOPSIS	TOPSIS		
Goal Programming			
DEA	DEA		

Each method has unique particularities, limitations, and perspectives depending on the situation. To choose the suitable method, experts recommend first analyzing the inputs (data provided from each project) and modelling effort required and the solution provided by each method (Table 2-2).

Table 2-2 Inputs, effort required, and outputs for eight multi-criteria decision-making methods (adapted from Ozcer, 2021)

Method	Input	Effort Required	Output
MAUT	Utility function	Very High	Complete ranking with scores
ANP	Pairwise comparisons on a ratio scale and interdependencies	↑	Complete ranking with scores
MACBETH	Pairwise comparisons on an interval scale		Complete ranking with scores
AHP	Pairwise comparisons on a ratio scale		Complete ranking with scores
ELECTRE	Indifference, preference, and veto thresholds		Partial and complete ranking (pairwise outranking degrees)
PROMETHEE	Indifference and preference thresholds		Partial and complete ranking (pairwise preference degrees and scores)
Goal programming	Ideal option and constraints		Feasible solution with deviation score
TOPSIS	Ideal and anti-ideal option	↓	Complete ranking with closeness score
DEA	No subjective inputs required	Very Low	Partial ranking with effectiveness score

3. Methodology

Three methods are applied to show potential PM and project PM applications in the mineral industries through case studies: the Markowitz model (modern portfolio theory), Kataoka's model, and the UTA method. Markowitz's method is selected because it provides a systematic approach to portfolio construction, considering the risk-return tradeoff and the benefits of diversification. It helps investors optimize their portfolios based on risk preferences, goals, and available options. On the other hand, Kataoka's method aims to minimize the probability of portfolio returns falling below a certain threshold or target level. It is used to construct portfolios that emphasize downside protection while aiming to achieve a reasonable level of return. In addition, the UTA method is used in portfolio selection because it offers a systematic approach to incorporate multiple criteria, preferences, and uncertainties. It allows for personalized and informed decision-making, considering the investor's objectives and expertise.

The first stage of the research is based on two case studies focused on mining company decision problems (Figure *3-1*). The "sales strategy" case study shows how a decision problem within a mining department is solved using PM tools. The input data are prices obtained by mean reversion simulation and the prices released by the analytics group, Fitch Solutions. The "multi-division project portfolio selection in a mining operation" reflects the diversity of project objectives in a mining operation. The dataset was provided by a decision-making group. Both case studies apply, analyze, and compare the Markowitz and Kataoka's models. The third case study represents an international mining corporation needing to evaluate multiple criteria to make a decision. The UTA was selected. An additive utility function based on a reference dataset is used.

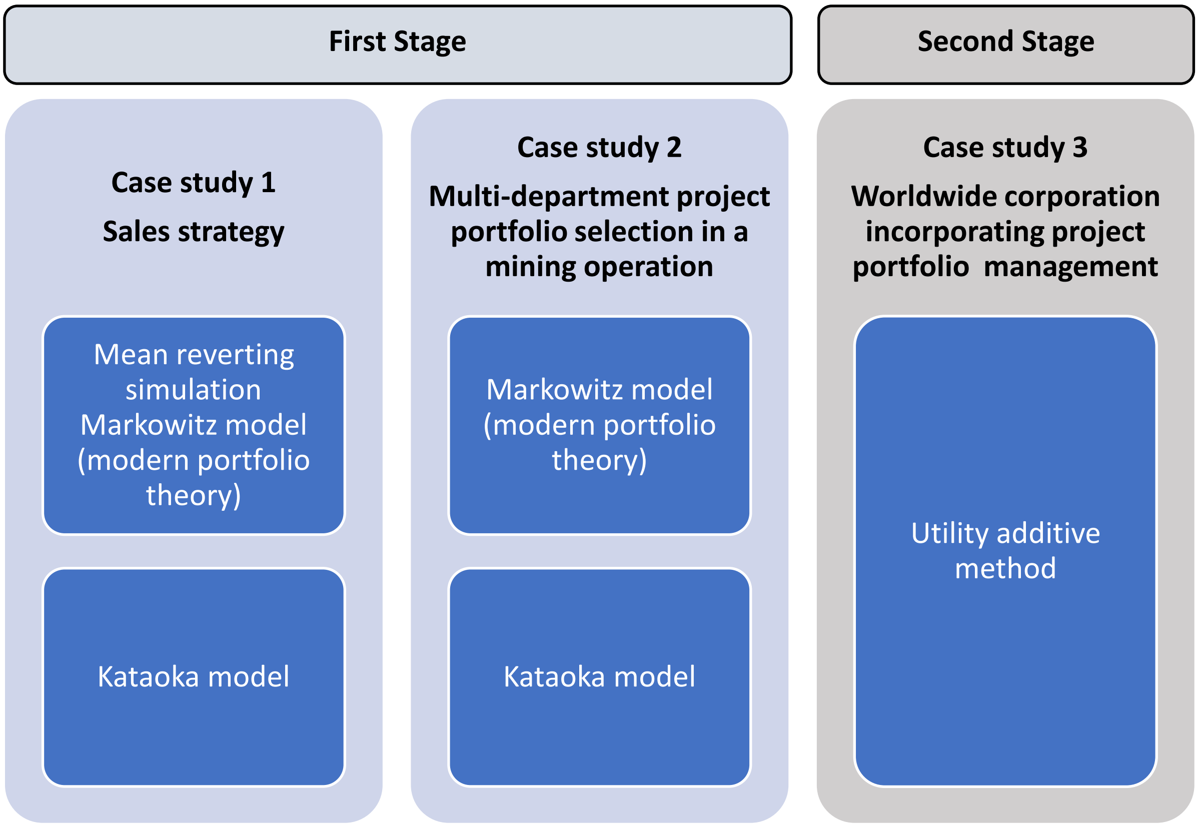


Figure 3-1 Case studies and methods used for evaluation.

3.1. Mean Reversion Simulation

Mean reversion is a stochastic simulation technique used in commodity price analysis. It is a common statistical analysis method to investigate market conditions. The underlying principle is that an asset price tends to converge on the average price over time. In other words, historical data returns and asset price volatility will eventually return to the long-term mean of the entire dataset. Mean reversion is the process by which prices that have increased steadily over time return to their initial level.

Mean reversion theory has led to a variety of investment methods involving buying and selling financial assets having recent performances that deviate significantly from their historical averages. These models include a long-term trend that functions as an attractor, causing the process to oscillate around it, as well as a random element that increases the movement volatility. According to the trend structure and the process volatility, the models' specific properties will vary.

The mean reversion model used in this study is the Ornstein-Uhlenbeck model, which assumes that all process parameters are constant (Equation 3.1):

$$dx_t = k(\theta - x_t)d_t + \sigma\sqrt{x_t}dz_t \tag{3.1}$$

Where the parameter "x_0" is the simulation initial status at time zero, t_0.

Let $y = a + bv$ be the equation produced by fitting a trendline to the historical data versus the previous period data plot with a standard error (SE), where y is the historical data change, v is the previous period data, a is the intercept, and b is the slope. Then, k, the mean-reversion factor, is calculated as b. θ is the long-term mean of the simulation calculated by a/b, and σ is the constant volatility parameter calculated as SE/θ. Finally, $dz = \varepsilon\sqrt{dt}$ represents the standard Brownian motion, where ε is a random value following the standardized normal distribution, and dt is the time increment.

3.2. Markowitz Model

The Markowitz model is among the most common methods to develop an investment portfolio, considering risk and return. The modern portfolio theory of Markowitz states that an efficient portfolio is expected to yield the lowest risk for a given level of return (Markowitz, 1971). An asset's attributes differ from a portfolio's attributes. Thus, the risk of two given assets is not the same as that of the same assets individually. The variance of each asset represents the risk index. Thus, the variability of each asset and covariance between the returns must be considered for the portfolio.

An investor will be interested in earning a constant expected value. The problem is a quadratic programming problem formulated by first minimizing the variance using Equation 3.2 (Inuiguchi & Ramik, 1998):

$$Variance(r) = V\left(\sum_{i=1}^{n} r_i x_i\right) = \sum_{i=1}^{n} \sigma_i^2 {x_i}^2 \tag{3.2}$$

Where x_i is the decision variable that represents the percentage of the investment to put into the asset i, r_i is the expected return rate of asset i, and σ_i^2 is the variance.

The expected return is a constant, c, which is formulated in Equation 3.3:

$$\sum_{i=1}^{n} r_i x_i = c \tag{3.3}$$

The percentage rate invested in each asset should be positive and the percentage invested should be 100% (Equation 3.4).

$$\sum_{i=1}^{n} x_i = 1 \quad x_i \geq 0, i = 1,2,3,..,n \tag{3.4}$$

Portfolio analysis begins with information related to the securities and ends with a solution pertaining to the portfolio (all securities together). Different types of information about the securities can be used as starting material. A well-known source used is the past performance of the security.

Security investments have two essential features: uncertainty and correlation. Uncertainties are present because economic forces are not understood well enough for accurate predictions. However, some uncertainties are unrelated to economic influences and change the expected prosperity. Correlation among security returns gives information about whether diversification could eliminate or reduce the risk. Figure *3-2* summarizes the features of security investments and how they influence a portfolio’s construction.

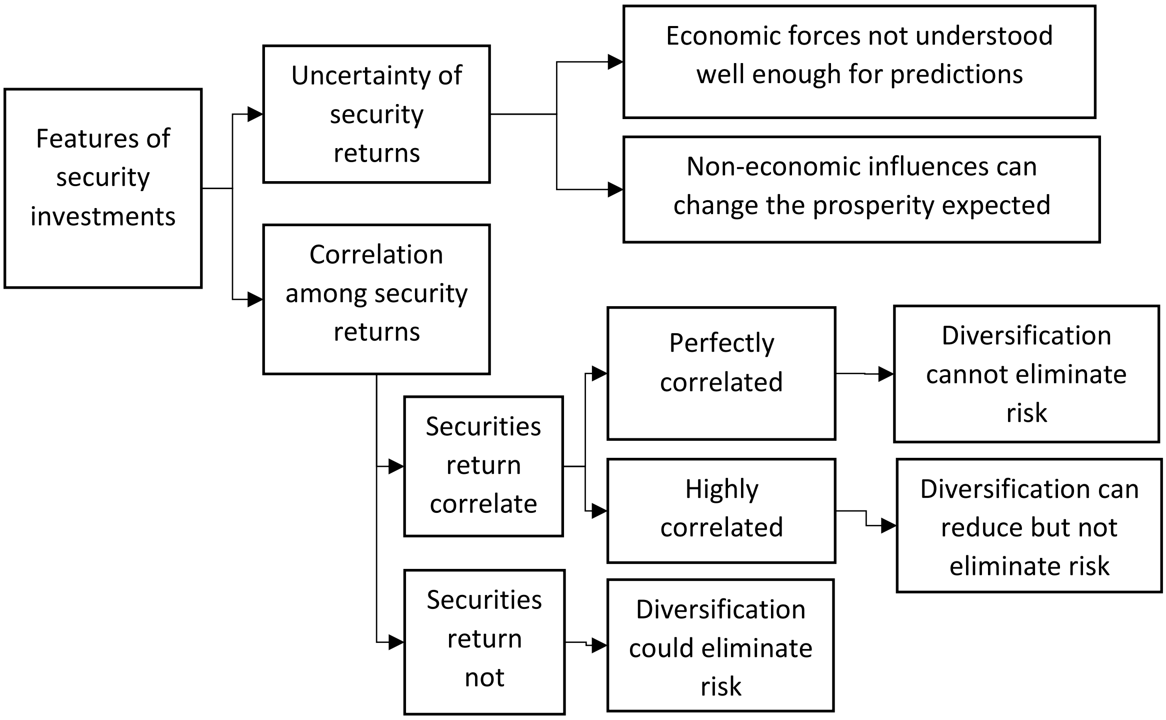


Figure 3-2 Features of security investments (adapted from Markowitz, 1971)

3.3. Kataoka's Model

Kataoka (1963) proposed a model for investors who seek a portfolio that protects the lowest return they can accept. The probability that the portfolio return is smaller than the lowest accepted return must not be higher than a set value (Francis & Kim, 2013). This constraint can be expressed mathematically in Equation 3.5:

$$Prob\ (R_P < R_L) \leq \alpha \tag{3.5}$$

Where, R_p represents the portfolio return, R_L is the target return for the investments set for the investors and represents the minimum level of return known as the safety threshold or the disaster level, and α is an admissible limit on the probability of failing to get the minimum level of return accepted (R_L). Assuming that the returns are normally distributed, Kataoka's model can be studied in a mean-variance context. Then, Equation 3.5 can be converted as Equation 3.6, where k_α is found from the normal distribution table for a specified reliability level, and σ_P represents the standard deviation from the portfolio.

$$Prob\left(k_\alpha \leq \frac{R_L - R_P}{\sigma_P}\right) \leq \alpha \tag{3.6}$$

In Figure *3-3*, the shaded area specifies the probability that the return is lower than R_L. k_α is simply determined from a standard normal distribution table (Francis & Kim, 2013).

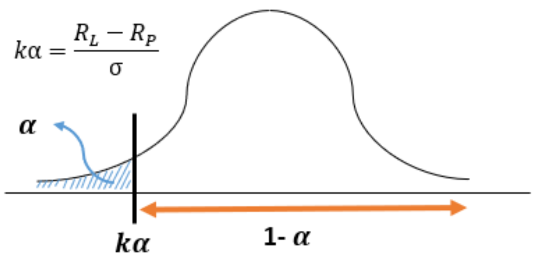


Figure 3-3 Lowest return representation

Finally, the formulation of Kataoka's Model is reduced as Equation 3.7:

Maximize

$$R_L = \sum_{i=1}^{n} r_i x_i + k_\alpha \sqrt{\sum_{i=1}^{n} {\sigma_i}^2 {x_i}^2} \tag{3.7}$$

Subject to Equations 3.8 and 3.9:

$$\sum_{i=1}^{n} r_i x_i \tag{3.8}$$

$$\sum_{i=1}^{n} x_i \quad x_i \geq 0, i = 1,2,3,..,n \tag{3.9}$$

3.4. Multi-attribute Utility Theory

The methods described in the sections above are based on two principal project criteria: maximizing return and minimizing risk. However, mining projects may have more criteria to evaluate and require an MCDM tool like the UTA. Figure *3-4* shows how research is directed from the Markowitz and Kataoka models to the UTA model.

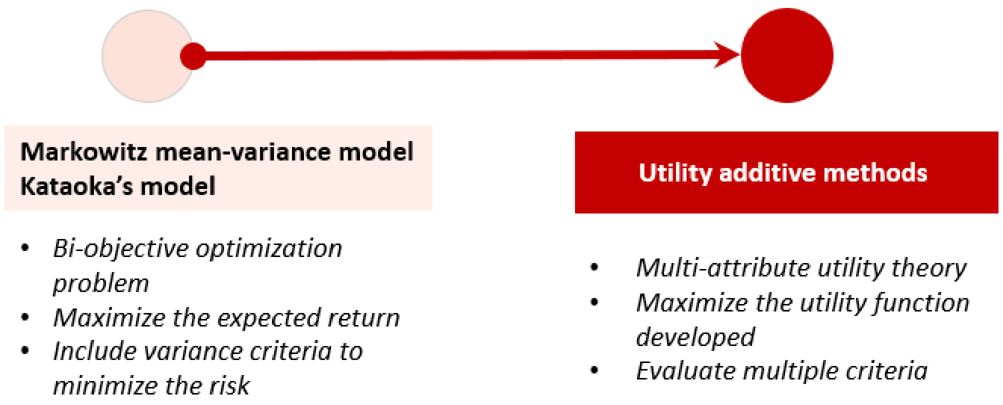


Figure 3-4 Methods used in the research and principal features.

Despite the level of effort required (Table *2-2*), we find it crucial to employ this method due to its effectiveness in estimating the connection between the maximal solutions of the proposed projects and the corporate strategy. The UTA utilizes an additive value system, known as preference disaggregation-aggregation analysis, to accomplish this task successfully. It uses linear programming optimization to facilitate management of the impact of external factors and business constraints (Figure *3-5*).

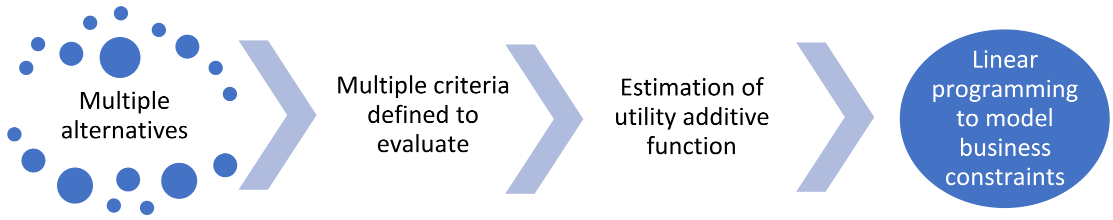


Figure 3-5 Methodology for utility additive method of project portfolio selection

The proposed UTA model is based on comparison and analysis of a set of projects respecting *i* criteria involved in project performance. The vector c$\{c_1, c_2, c_3, c_4, \dots c_i\}$ is the vector for the *i* criteria. Equation 3.10 represents the utility function, $U(c)$:

$$U(c) = \sum_{i=1}^{n} p_i u_i(c_i) \tag{3.10}$$

With the constraints:

$$\sum_{i=1}^{n} p_i = 1 \text{ and } u_i(c_i) > 0$$

Where, $u_i(c_i)$ is the partial utility of each criterion (also called the marginal value function), and p_i indicates the weight assigned to each $u_i(c_i)$.

The additive utility function implies that $u_i(c_i)$ values are calculated only considering the given criterion: the value of each increases with the value of the criterion. Next, as shown in Figure *3-6*, the function $U(c)$ satisfies an aggregation of the criteria in a shared index to compare the projects (Beuthe & Scannella, 2001). The most and least favored value are identified as $c\ [c_{i(min)}, c_{i(max)}]$ and divided into *m* intervals that the analyst considers adequate (Figure 3-7).

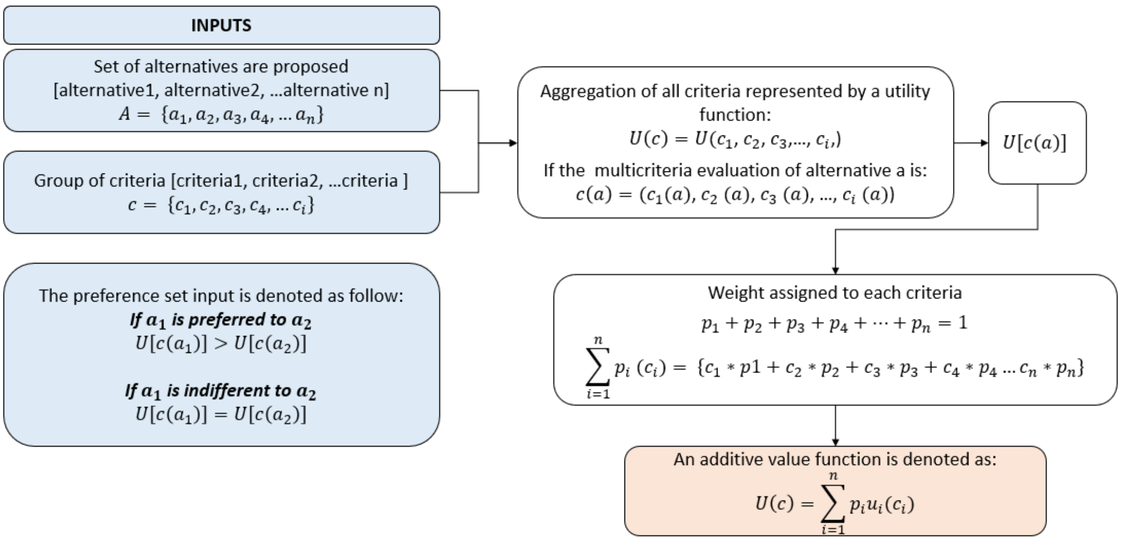


Figure 3-6 Inputs and process to obtain the additive utility function, U(c).

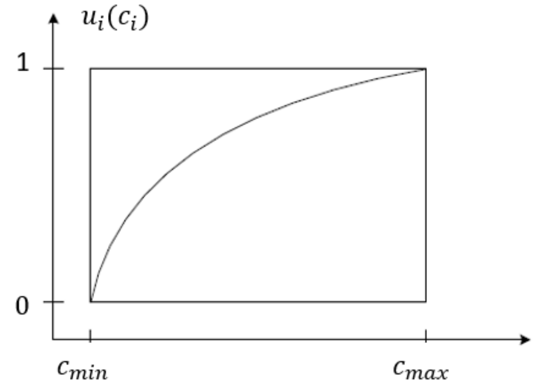


Figure 3-7 Normalized marginal value function.

The marginal utility function is created to remodel the scale to {0–1} for each criterion as follows (Equation 11):

$$\sum_{i=1}^{n} u_i\big(c_i(max)\big) = 1 \quad \text{and} \quad u_i\big(c_i(min)\big) = 0 \tag{3.11}$$

$$\forall\, i = 1,2,3, \dots n$$

Considering that each criterion has *m* intervals, the total number of fraction is *j*, c_i^j, is identified as the end point of fraction *j* and can be calculated using Equation 3.12:

$$c_i^j = c_{min} + \frac{j-1}{m}(c_{max} - c_{min}) \tag{3.12}$$

Furthermore, the partial utilities are estimated for each criterion as in Equation 3.13:

$$u_i(c_i(a)) = u_i(c_i^j) + \frac{c_i(a) - c_i^j}{c_i^{j+1} - c_i^j}(u_i(c_i^{j+1}) - u_i(c_i^j) \tag{3.13}$$

UTA assesses the function $U(c)$ provided in Equation 3.10 over a set of reference projects. The reference set is provided by the management team and is expressed as a set of proposed alternatives [alternative 1, alternative 2, …alternative z] $A' = \{a_1, a_2, a_3, a_4, \dots a_z\}$

If $\boldsymbol{a_1}$ ***is preferred to*** $\boldsymbol{a_2}$: $U[c(a_1)] > U[c(a_2)]$

If $\boldsymbol{a_1}$ ***is indifferent to*** $\boldsymbol{a_2}$***:*** $U[c(a_1)] = U[c(a_2)]$

Then, the approximated utility of each alternative, a, belonging to A' is approximated using Equation 3.14.

$$U'c(a) = \sum_{i=1}^{n} u_i(c_i(a)) + \sigma(a) \tag{3.14}$$

Where, $\sigma(a)$ is a positive potential error referring to each utility of each alternative, a. The goal of the UTA is to minimize the sum of these errors (Equation 3.15).

$$F = \sum_{a \in A'} \sigma(a) \tag{3.15}$$

A variation of UTA, the UTA-STAR model, was proposed by Siskos and Yannacopolous (1985). This method introduces a double error to be minimized. It is calculated using Equation 3.16.

$$U(a_k) = \sum_{i=1}^{n} u_i(c_i(a_k)) - (-\sigma^+(a_k) + \sigma^-(a_k)) \tag{3.16}$$

where σ⁺ and σ⁻ are the over- and under-estimation error, respectively. The value of the reference set is reduced as in Equation 3.17 and written for each par of reference:

$$\Delta(a_k, a_{k+1}) = u_i(c_i(a_k)) - (\sigma^+(a_k) + \sigma^-(a_k) - ((u_i(c_i(a_{k+1})) - (\sigma^+(a_{k+1}) + \sigma^-(a_{k+1})) \tag{3.17}$$

Finally, linear programming solve is used to minimize the sumn of errors (Equation 3.18):

$$Min \sum_{k=1}^{n} (\sigma^+(a_k) + \sigma^-(a_k)) \tag{3.18}$$

Subject to:

$$\left.\begin{array}{l} \Delta(a_k, a_{k+1}) \geq \delta \ if \ \ a_k > a_{k+1} \\ \Delta(a_k, a_{k+1}) = 0 \ if \ \ a_k \sim a_{k+1} \end{array}\right\} \ \forall k$$

Where, δ is a small positive number to assure the preference between the projects. And:

$$u_i c_i(a) \geq 0 \ , \sigma^+(a_k) \geq 0 \ , \ \sigma^-(a_k) \geq 0$$

With the utilities found after minimizing the errors, a second linear programming optimization adapts the model to the business strategies and other constraints.

4. Case Study 1: Sales Strategy Based on Modern Portfolio Theory

4.1. Case Study 1 Description

A gold mining corporation has an annual gold production of 200,000 oz. The corporation makes sales agreements to maximize revenues and minimize price risks. In a highly fluctuating market, the corporation can sell a certain quantity of their products in future markets to hedge the price risk. For example, in a commodity swap, it can exchange cash flows associated with commodity sales with another corporation risk. This option also provides an opportunity to extend short-term liabilities. When demand for a mineral product is high, sales in auction markets can be another avenue to increase revenues.

The gold mining corporation aims to generate 11% return with a minimum risk through a sales strategy comprising four sales options (Table 4-1): 1) spot market, 2) future market, 3) swap market, and 4), auction market. Each option offers a different future price for the 10-year project term. In addition, the board director has stated that total sales production could be split into different markets to maximize revenue.

Table 4-1 Market option descriptions (from Priolon, 2019)

Option	Description
Spot	Commodities are sold directly and immediately to buyers. The transaction is undertaken at a price called spot price or physical price.
Future	Negotiated in organized markets, a future contract is a commitment to exchange a commodity at a determined price on a future date.
Swap	Contract where two operators exchange cash flows. Operator A commits to paying in a determined time at determined time intervals. Operator B commits to paying a stable flow stated at the beginning of the contract.
Auction	Sellers and purchasers make a bid or offer in an auction market. Trade occurs when a seller has acceptable lowest prices, and a purchaser pays the highest price.

4.2. Case Study 1 Solution Framework

The first task is to forecast the commodity prices for the four proposed markets that will be used as inputs to the decision-making process (Figure *4-1*). Next, the decision variables, constraints, and objective function are defined. The objective function of the covariance matrix calculated from the forecasted return is limited. The next step is to develop the methodologies from Sections 3.2 and 3.3. Finally, results are interpreted.

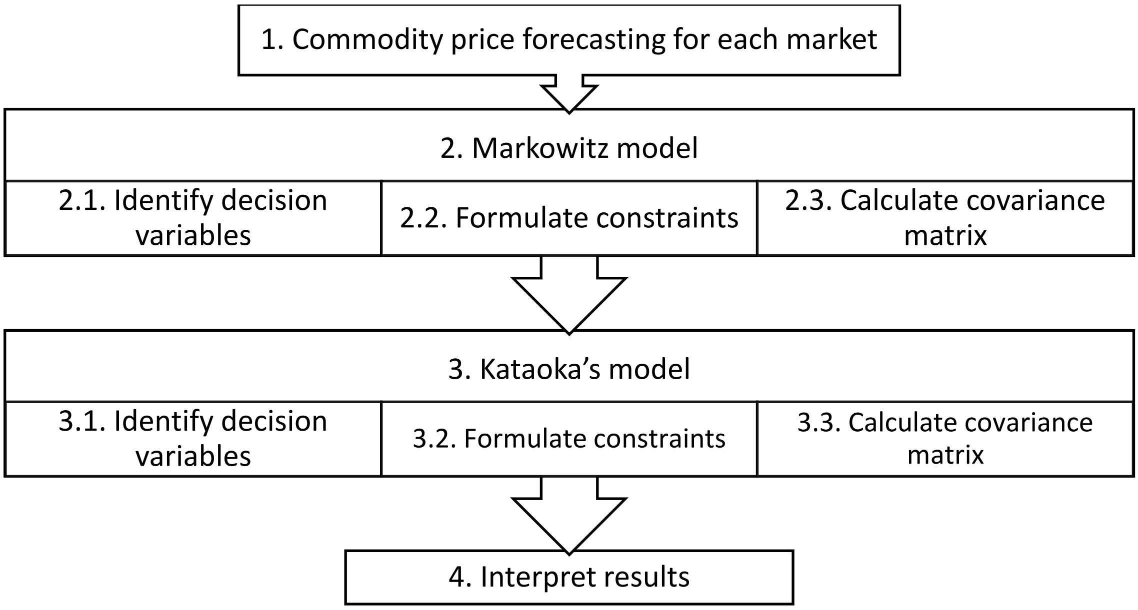


Figure 4-1 Case study 1: Solution process

4.3. Price Simulation

Mean reversion simulation was applied to estimate spot market prices, mean reverting simulation is applied, as it was introduced in section 3.1 because gold prices have historically exhibited mean reversion tendencies. Furthermore, gold is often considered a long-term investment and a store of value. By using mean reversion simulation, investors can gain an understanding of the potential long-term trends and cycles in gold prices. This can be valuable for investors who are looking to make strategic decisions regarding their gold investments over extended periods.

The historical gold prices shown in Table 4-2 were used. Recall from Section 3.1, $y = a + bv$ is the equation produced by fitting a trendline to the historical data change $(x_t - x_{t-1})$ versus the previous period data (x_{t-1}), where y is the historical data change, v is the previous period's data, a is the intercept, and b is the slope. The mean-reversion factor (k), the long term mean of the simulation (θ), and the constant volatility parameter (σ) are calculated, as shown in Table 4-3.

Table 4-2 Historical annual gold prices from 2012 to 2021

Year	Gold Price (x_t)	(x_t - x_{t-1})	(x_{t-1})
2012	1668.98		
2013	1411.23	−257.75	1668.98
2014	1266.40	−144.83	1411.23
2015	1160.06	−106.34	1266.40
2016	1250.80	90.74	1160.06
2017	1257.15	6.35	1250.80
2018	1268.49	11.34	1257.15
2019	1392.60	124.11	1268.49
2020	1769.59	376.99	1392.60
2021	1798.61	29.02	1769.59

Table 4-3 Mean reverting parameters

Parameter	Values
b	−0.2552
a	367.3209
RSE	185.6858
x_0	1798.61
k	0.255
θ	1,439.247
σ	0.129
T (time in years)	10
Δt	1

The spot prices obtained from the simulation are shown in Table 4-4 along with future market prices from studies released by Fitch Solutions (Wulandari & Drozdovica, 2022). Based on expert opinions, swap prices were calculated considering –5% of the spot markets values, while auction prices were considered as +2% from future contracts. Figure *4-2* summarizes the prices for the four market options. Table 4-5 shows the returns per year calculated by multiplying yearly production by the forecasted prices in Table 4-4.

Table 4-4 Future prices set by each market option.

	Price Au (US$/oz)									
Option	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Spot	1,799	1,706	1,638	1,589	1,553	1,522	1,502	1,485	1,475	1,464
Future	1,785	1,711	1,663	1,623	1,584	1,584	1,584	1,584	1,584	1,394
Swap	1,727	1,638	1,573	1,541	1,506	1,446	1,427	1,411	1,401	1,391
Auction	1,821	1,745	1,680	1,639	1,600	1,568	1,568	1,568	1,568	1,380

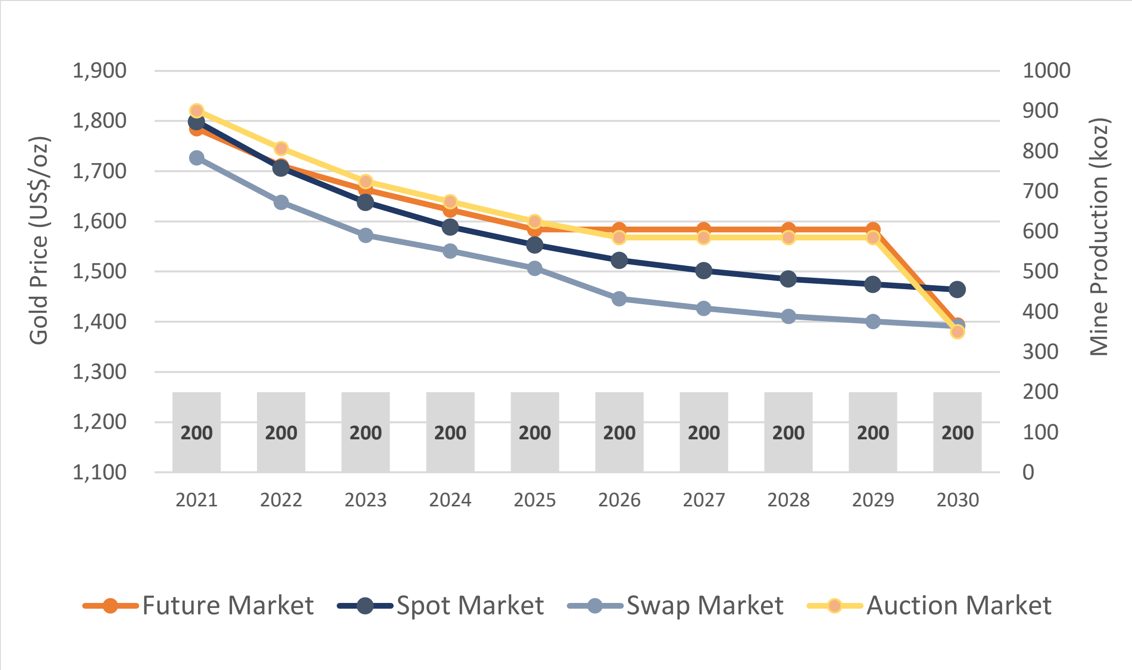


Figure 4-2 Simulated average gold prices for four sales strategies; grey bars represent mine production in kilo ounces (koz)

Table 4-5 Returns per year for market option

Returns per year (million US$)											
Option	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**Average**
Spot	360	355	366	357	365	370	365	357	352	354	360.5
Future	363	363	363	360	362	358	358	360	359	359	360.1
Swap	367	367	367	367	360	350	365	360	362	364	362.9
Auction	358	356	354	352	350	348	346	370	368	366	356.8

4.4. Markowitz Model

The first step of modelling the problem is to describe the decision variables involved. As four market options are proposed to sell the gold production, it is assumed that each market takes the place of an asset to invest; the decision variables for the problem are:

- $m_1 = proportion\ of\ the\ production\ sold\ in\ spot\ markets$
- $m_2 = proportion\ of\ the\ production\ sold\ in\ future\ markets$
- $m_3 = proportion\ of\ the\ production\ sold\ in\ swap\ markets$
- $m_4 = proportion\ of\ the\ production\ sold\ in\ auction\ markets$

The second step involves identifying the constraints explained in the case study to describe the total production sales and the expected return. For the total production limitation (Section 4.1) is that the total annual production must be sold. Thus, proportions represented in the decision variables must total 100% of the production. Considering that m_i is the decision variable explained above, it is represented as follows (Equation 4.1):

$$\sum_{i=1}^{n} m_i = 1 \tag{4.1}$$

Where, n is the number of market options. Considering that each decision variable is positive (Equation 4.2):

$$m_i \geq 0,\ i = 1,2,3,4 \tag{4.2}$$

The mining corporation expects to earn at least 11% return (Section 4.1). Having r_i as the expected return of selling the production in the respective market, m_i, this constraint is represented as follows (Equation 4.3):

$$\sum_{i=1}^{n} r_i m_i \geq 11 \tag{4.3}$$

The third step is formulating the objective function such that the risk is minimized.

$$Variance(r) = \sum_{i=1}^{n} \sigma_i^2 {x_i}^2 \tag{4.4}$$

Using data in Table 4-5, the covariance matrix of each sales strategy is calculated (Table 4-6), where the lowest covariance value is bold.

Table 4-6 Covariance matrix for forecasted market options

Covariance matrix				
Market	**Spot**	**Future**	**Swap**	**Auction**
Spot	441.7	**354.6**	448.6	434.6
Future	**354.6**	375.4	**358.4**	435.6
Swap	448.6	**358.4**	459.9	442.6
Auction	434.6	435.6	442.6	512.9

The model is a quadratic programming problem. It is solved by *a Quadratic Programming Problem* routine *in CPLEX STUDIO*. The optimal sales portfolio to produce a risk index of 19.37 is: fraction $m_1 = 0.19\%$ of the production in spot markets; $m_2 = 0.81\%$ of the production in future markets.

The future market appears to provide the lowest risk index of 19.37 (Figure 4-3). The auction market provides the highest revenue (US$322.75 million), but it has the highest risk index of 22.65. The spot market is riskier and has a lower revenue than the future market. The best option is to sell 100% of the production in the future market. However, Markowitz's optimization shows that selling the 19% of the production in the spot market and 81% of the production in the future market can reduce the risk index from 19.37 to 19.27, though the return is reduced by US$1.38 million.

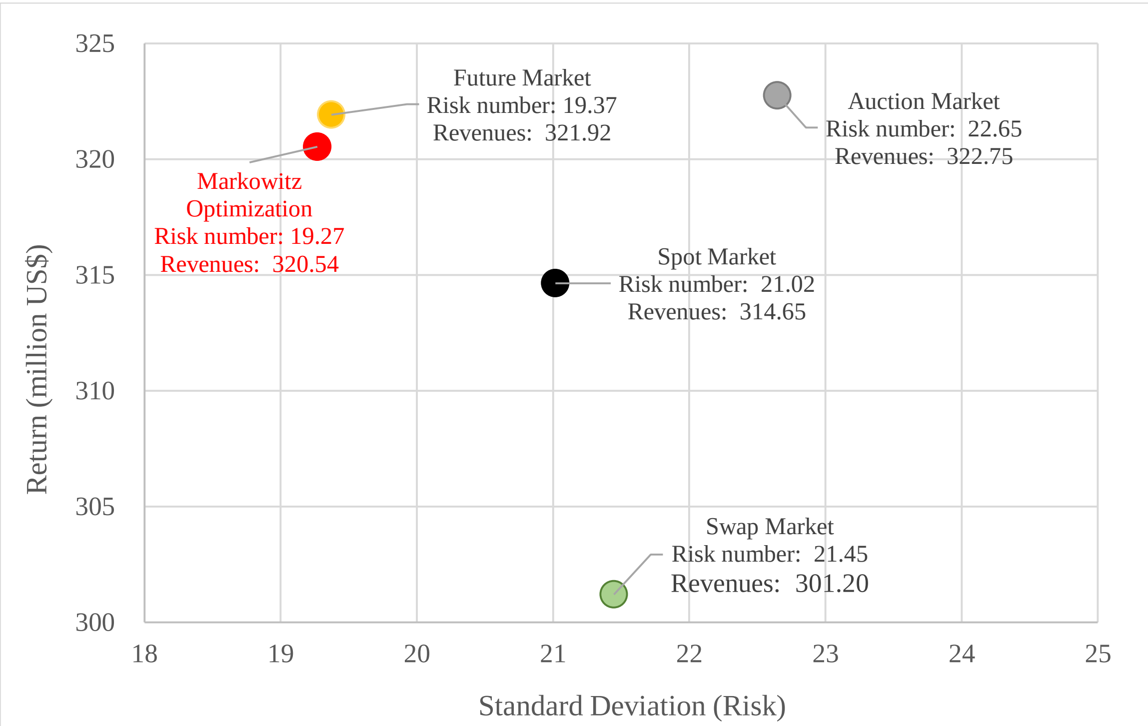


Figure 4-3 Risk and return levels of selling 100% of the production individually in each of four markets compared to the Markowitz optimization.

If the marketing department of the corporation is focused on reducing the risk of its sales, diversification is the best option. On the other hand, if it is focused the highest return, selling 100% of the production in the future market is the best option because the investor will avoid a loss of 1.38M$ and accept a higher risk.

4.5. Kataoka Model

As explained in Section 3.2, Kataoka's Model attempts to manage the risk for a predetermined return. The initial problem-solving step is to establish the level of risk that the corporation aims to avoid. The corporation in this case study has a confidence level of 95%. Thus, the insured level objective to maximize is determined by Equation 4.5.

$$R_L = \sum_{i=1}^{n} r_i x_i + k_\alpha \sqrt{\sum_{i=1}^{n} {\sigma_i}^2 {x_i}^2} \tag{4.5}$$

At α = 5%, k_α = –1.645.

As described in Section 4.1, the constraints are the total production sales (Equation 4.6), and the expected constant return (Equation 4.7). Thus, proportions represented in the decision variables must total 100% of the production. Considering that m_i is the decision variable explained, it is represented as follows:

$$\sum_{i=1}^{n} m_i = 1 \tag{4.6}$$

Where n is the number of market options. Each decision variable is positive:

$$m_i \geq 0,\ i = 1,2,3,4 \tag{4.7}$$

Also, the section 4.1 explains that the mining corporation expects to earn at least 11% of their return, having r_i as the expected return of selling the production in the market i, and:

$$\sum_{i=1}^{n} r_i m_i \geq 11 \tag{4.8}$$

After distinguishing the decision variables, formulating the linear constraints, and establishing the root quadratic equation to maximize, the problem is ready to be solved. Using the exponential solver problem in *BARON*, we see that an optimal sales portfolio should sell a fraction ($m_1 = 0.42$) of the production in spot markets, $m_2 = 0.24$ in future markets, $m_3 = 0.02$ in auction markets, and $m_4 = 0.32$ in swap markets to produce a risk index of 20.59 and a revenue of US$318.72 million (Figure *4-4*). If the marketing department is focused on a safety portfolio of its sales, Kataoka's model is the best approach.

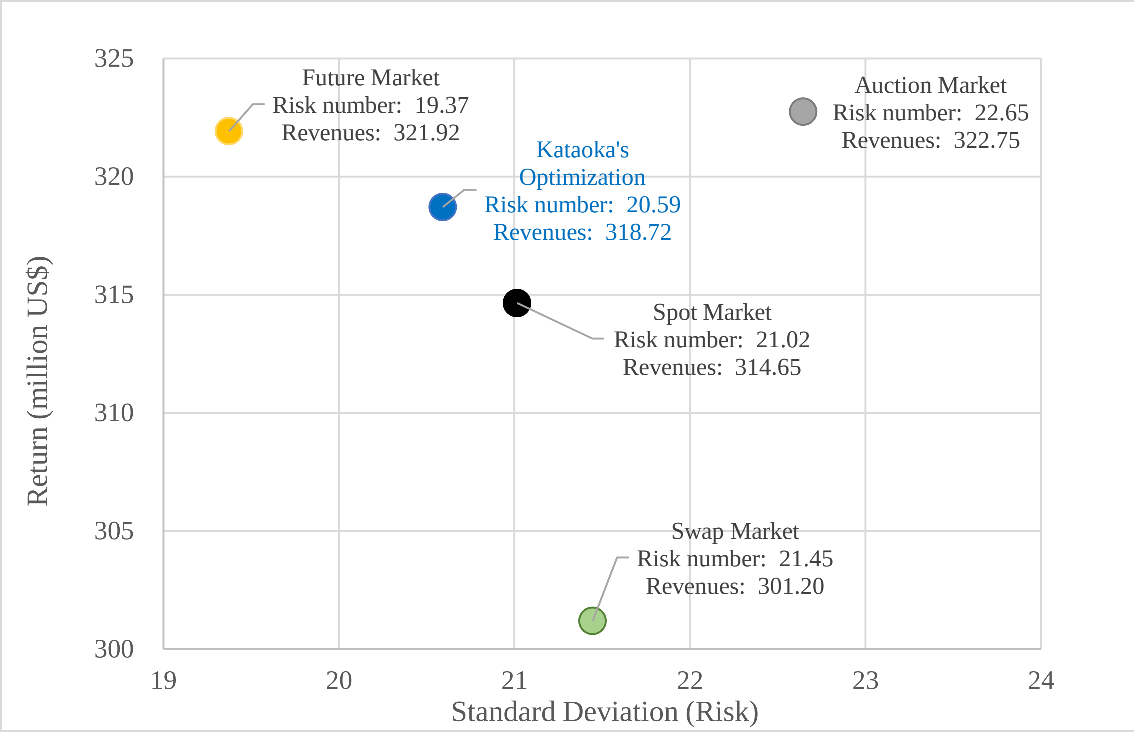


Figure 4-4 Risk and return levels of selling 42, 32, 24, and 2% of the production in spot, future, swap, and auction markets, respectively, compared to Kataoka optimization.

4.6. Discussion of Two Models

Kataoka's model provides a sales strategy that ensures a portfolio with a higher confidence level of return (95%). Selling 42% of the production in spot markets and 24% of the production in the future market results in the lowest individual variability of these two markets (

Table 4-7).

Table 4-7 Standard deviation (SD) values using Kataoka's model

	Spot	Future	Swap	Auction
SD	21.017	19.374	21.446	22.647

In the Markowitz model, the choice is to sell the product only in the spot and future markets because the objective function is to minimize the covariance values (Table *4-6*), that is, minimize the risk. Thus, the diversification is focused only on these two markets. Kataoka's optimization produces a lower return than the Markowitz model (Figure *4-6*).

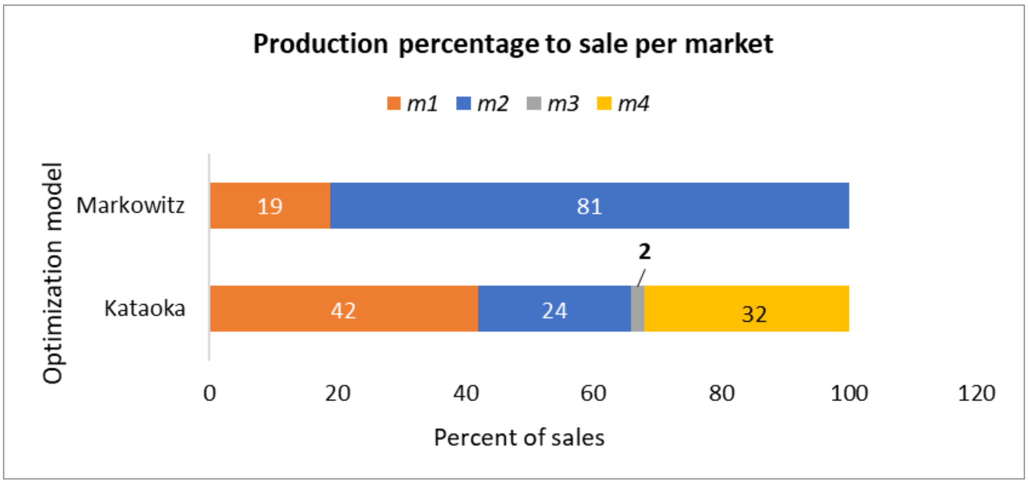


Figure 4-5 Production percentage to sell in each market for Markowitz and Kataoka models.

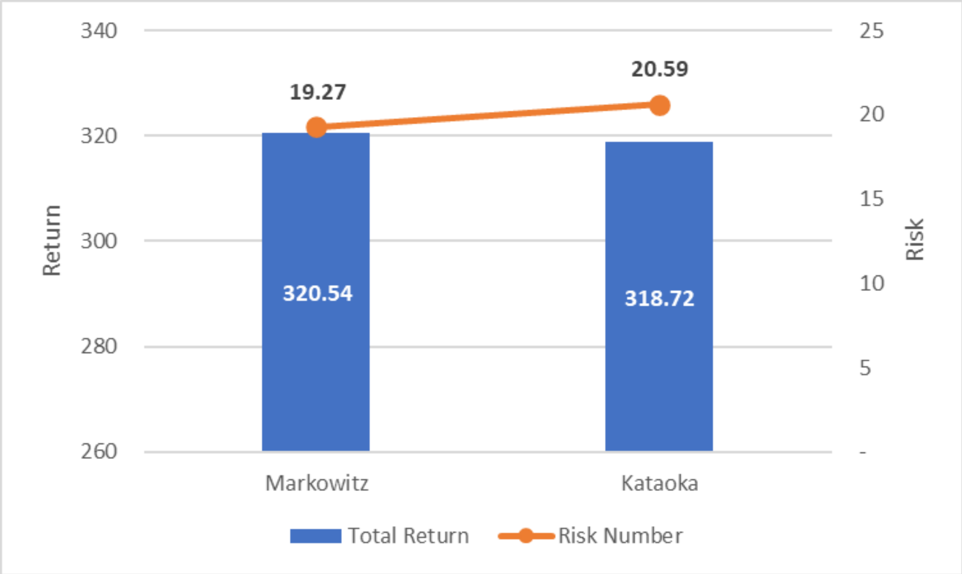


Figure 4-6 Case study 1: Risk and return results.

Although Kataoka’s optimization diversifies the portfolio more (Figure *4-5*), it presents a higher risk due to its emphasis on downside protection while aiming to achieve a reasonable level of return. Furthermore, this higher risk number minimizes the probability of the portfolio's actual return falling below this minimum acceptable return (95%).

Finally, it is concluded that two different results are proposed for allocating sales, considering risk, return, and diversification, which can also provide some advantages if other parameters are included. Providing more data to the board can lead the corporation to make the most convenient decision.

5. Case Study 2: Modern Portfolio Theory for Project Selection in a Mining Corporation

5.1. Case Study 2 Description

The second case study focuses on choosing project proposals to fund from various divisions of a mining corporation (e.g., energy, precious metals, industrial minerals). Every year, as a part of growth strategy, a set amount of financial resources (US$200 million in this case) is set aside to support a set number of projects (11 in this case) proposed by the business divisions. Determining the projects to be funded is a decision-making problem with the following criteria: the potential value of specific project, the historical performance of the division proposing a project, similarities between projects, and geographic and commodity risks. The task of corporate management is to select projects that align with the corporation's strategy, which is typically a blend of sustainability, profitability, energy transition, and social acceptance.

Projects 1 and 2 are competitive: the board must choose one of these proposals; both cannot be executed (Table 5-1). Projects 3–5 indirectly increase production, but they decrease safety and environmental risks. Project 6 has the potential t o add resources and reserves and add value to the corporation's shares. However, the campaign might not generate a positive outcome, so the risk is high. The new blasting design in Project 7 requires new equipment, a new budget, and supplies. The potential outcome will be higher efficiency (i.e., better particle size distribution, less dust, noise, and dilution). The equipment replacement in Project 8 will reduce costs and the required compliance and make the corporation more competitive. The new training program in Project 9 aims to improve safety culture in the mining operation through a new training program and is difficult to value, given that human safety, as an ethical issue, cannot be assigned a monetary value. Project 10 may include providing job opportunities to local people or constructing a road/hospital/school in the town near the mine. The new procurement/supply chain model in Project 11 would reduce waiting times due to delays of spare parts or labour.

Table 5-1 Project proposals received from divisions of a corporation

Project	Name	Description	Objective and Impact	Budget (million US$)	Potential Value (million US$)
1	Implement crushing and conveying system	Install new system to eliminate need to buy trucks to replace those at the end of life. New infrastructure requires new licenses and permits. Green technology and lower fuel consumption are major advantages.	Increase production Positive impact on environmental, safety, and social license (ESL) aspects	80	180
2	Buy trucks and shovels	Buy trucks and shovels to replace obsolete equipment and trucks at the end of life	Increase production Negative impact on ESL aspects	35	67
3	Maintenance strategy for a new processing plant	Improve processing plant, moving from preventive to predictive maintenance	Increase production and efficiency	10	35
4	Construct new waste dump	Increase capacity of waste dumps with a new monitoring system. New infrastructure requires additional licenses and permits.	Increase production Negative impact on ESL aspects	40	51
5	Increase tailings and water treatment facility capacities	Increase tailings pond capacity with new monitoring and safety systems. New infrastructure requires new licenses and permits.	Increase production Negative impact ESL aspects	50	68
6	Exploration drilling	New exploration campaign to potentially increase mine resources and reserves	Increase producton and/or extend life of mine	5	8
7	New blasting design	New blasting design to decrease loss and dilution	Increase efficiency	15	33
8	Purchase innovative equipment	New equipment to increase equipment availability and lower maintenance costs	Increase production and efficiency	27	42
9	Create new worker safety training program	New program to increase safety, consolidate safety culture, and lower costs associated with safety issues	Positive impact on ESL aspects	2	6
10	Social project	New project to promote relationship with community	Positive impact on ESL aspects	10	20
11	New logistics/buyer organizations	New logistic supply chain to minimize waiting times	Increase efficiency	8	14

5.2. Case Study 2 Solution Framework

The first step in solving case study 2 is defining the decision variables (Figure 5-1). Unlike the previous case, in which the decision variables were a proportion of the total limited budget, this theoretical scenario comprises a set of decision variables representing a "go" or "not go" choice. Later, the covariance matrix is designed based on the correlation matrix, and the standard deviation is identified by the analyst performing the decision-making process. The limited budget is addressed in scenario 1, while an unlimited budget is addressed in scenario 2.

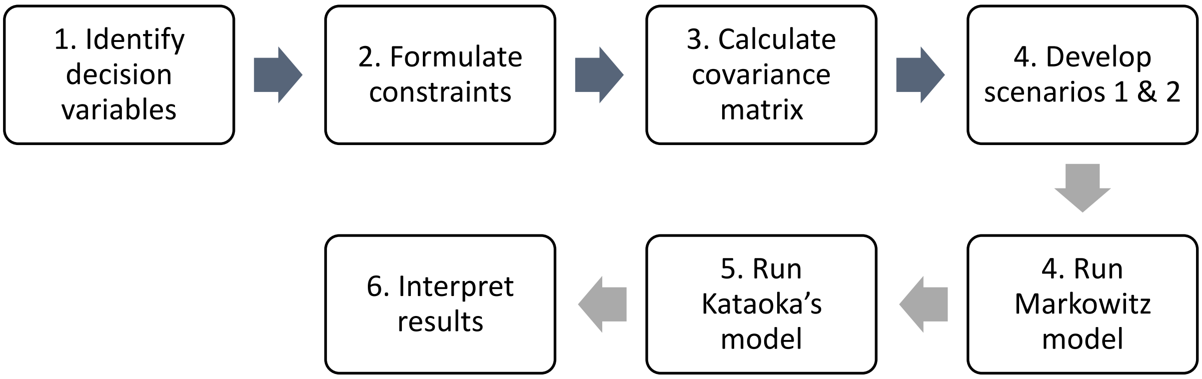


Figure 5-1 Case study 2: Solution process

5.3. Markowitz Model

The decision variable is notated as binary x_i. If project *i* is funded, the decision variable takes 1; otherwise, it is zero. A project must either be supported or not: there is no partial support. The first and one of the most important constraints is that the budget must be less than US$200 million, which is represented mathematically as in Equation 5.1:

$$\sum_{i=1}^{n} Budget_i \leq 200 \tag{5.1}$$

The second constraint is that the return must be greater than the budget provided:

$$\sum_{i=1}^{n} Return_i \geq 200 \quad (5.2)$$

The third constraint is the variability of the return (risk), which is represented by the covariance matrix. Covariances are estimated using Equation 5.3:

$$Variance(r) = \sum_{i=1}^{n}\sum_{j=1}^{n} \sigma_{i.j} x_i x_j \quad (5.3)$$

The other constraints are formulated in base of the interdependencies and features between the projects. We know that:

Project 1 and Project 2 are exclusive: $x_1 + x_2 <= 1$

Projects 3, 4, and 5 depend on Projects 1 or 2: $x_3 = x_1 + x_2$

$$x_4 = x_1 + x_2$$

$$x_5 = x_1 + x_2$$

5.3.1. Covariance Matrix (Risk)

To solve this problem, the covariance matrix to minimize the risk for the 11 projects is defined using the software, @Risk (Lumivero, Denver, CO), which calculates the distribution of each return and the correlation between the returns of each project (Figure *5-2*).

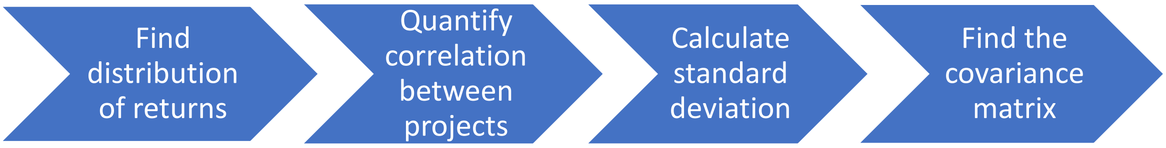
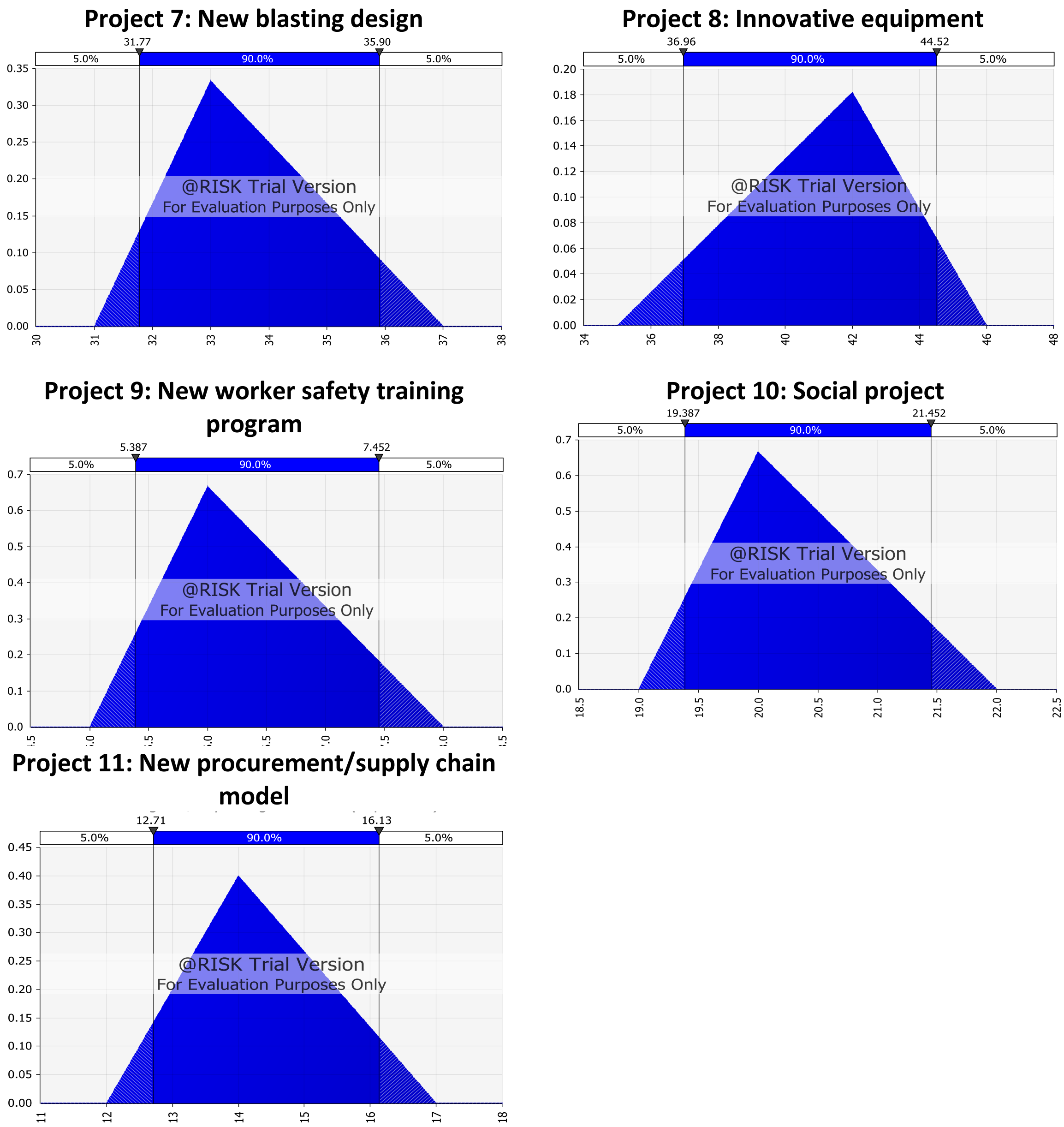
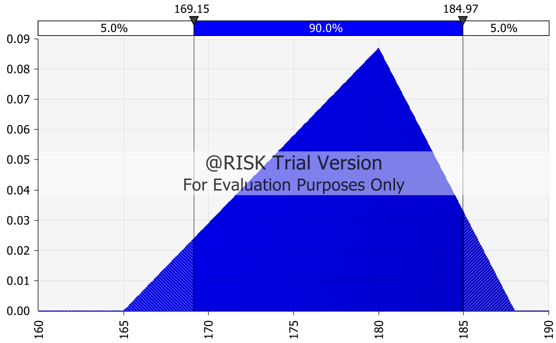


Figure 5-2 Case study 2: Process to build a covariance matrix in @Risk.

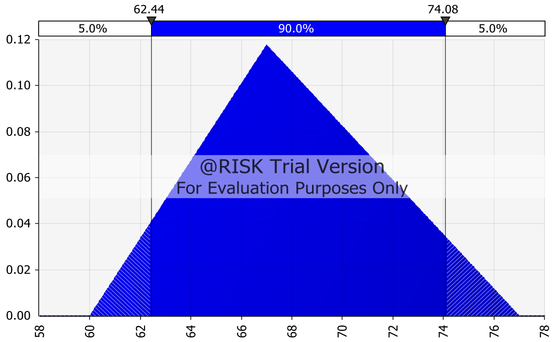
Because all projects are new, it is impossible to have information about past performance returns, so the estimate is made by the analyst, which in most cases, follows a triangular distribution for each project (Figure 5-3)



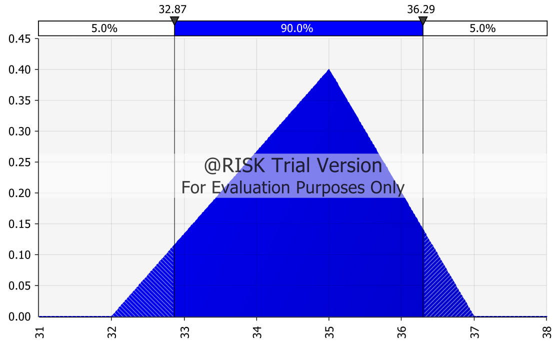
Project 1: Crushing and conveying system



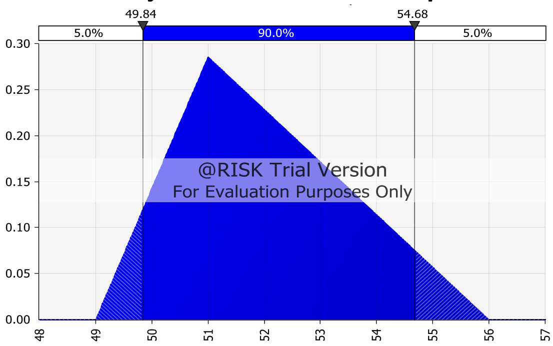
Project 2: Buy trucks and shovels



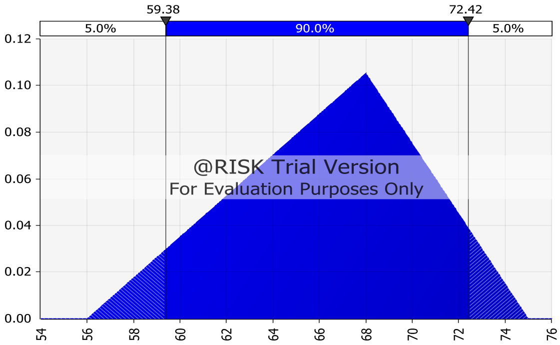
Project 3: Maintenance strategy



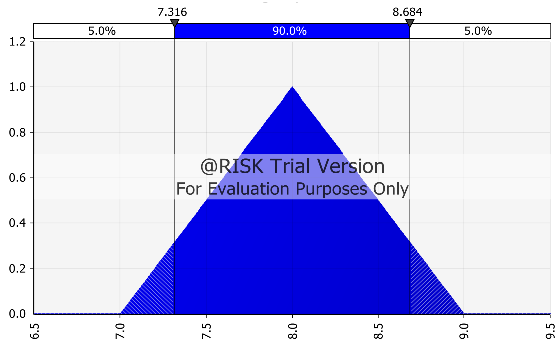
Project 4: New waste dump



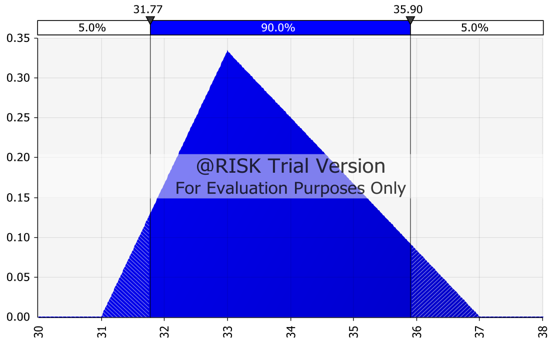
Project 5: Increase tailings/water facility



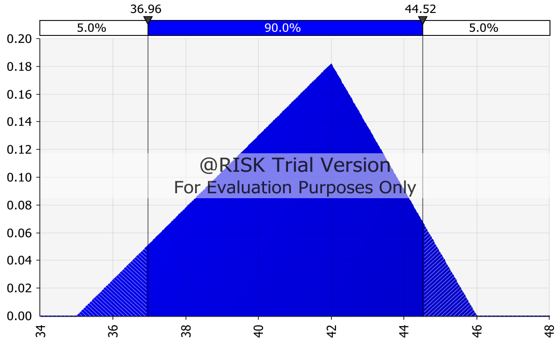
Project 6: Exploration drilling



Project 7: New blasting design



Project 8: Innovative equipment



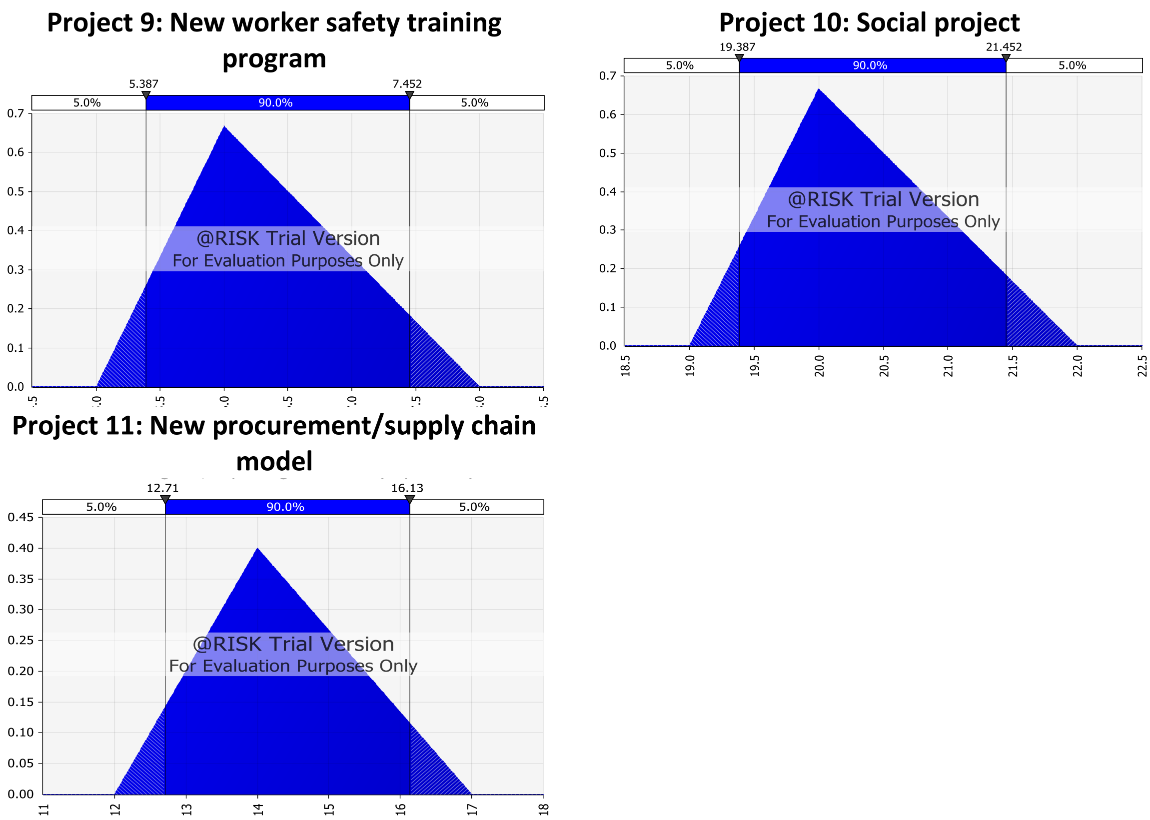


Figure 5-3 Case study 2: Distribution of returns for the 11 proposed projects

The objective and impact of each value are used to quantify the correlation between the returns of projects (Table *5-2*).

Table 5-2 Correlation coefficients between the returns for 11 proposed projects

Project	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1.000	0.340	0.388	0.146	0.097	0.340	0.583	0.583	0.340	0.728	0.728
2	0.340	1.000	0.680	0.486	0.243	0.777	0.583	0.583	0.777	0.388	0.388
3	0.388	0.680	1.000	0.388	0.194	0.680	0.486	0.486	0.680	0.243	0.243
4	0.146	0.486	0.388	1.000	0.680	0.486	0.097	0.097	0.291	0.146	0.146
5	0.097	0.243	0.194	0.680	1.000	0.243	0.049	0.049	0.243	0.019	0.019
6	0.340	0.777	0.680	0.486	0.243	1.000	0.486	0.486	0.874	0.291	0.291
7	0.583	0.583	0.486	0.097	0.049	0.486	1.000	0.874	0.486	0.291	0.291
8	0.583	0.583	0.486	0.097	0.049	0.486	0.874	1.000	0.486	0.583	0.583
9	0.340	0.777	0.680	0.291	0.243	0.874	0.486	0.486	1.000	0.291	0.291
10	0.728	0.388	0.243	0.146	0.019	0.291	0.291	0.583	0.291	1.000	0.874
11	0.728	0.388	0.243	0.146	0.019	0.291	0.291	0.583	0.291	0.874	1.000

The next step is to generate 5,000 simulations in @Risk to obtain 5,000 random numbers.

The standard deviation of each return is calculated (Table 5-3).

Table 5-3 Standard deviations (SD) for 11 proposed projects

	Project No.										
	1	2	3	4	5	6	7	8	9	10	11
SD	4.767	3.488	1.027	1.472	3.923	0.408	1.247	2.273	0.624	0.624	1.027

The covariance is calculated (Equation 5.4) to create the covariance matrix (Table 5-4).

$$Correlation = \frac{Cov(r_p, r_b)}{\sqrt{Var\ (r_b)}\ \sqrt{Var\ (r_p)}} \qquad (5.4)$$

Table 5-4 Covariance matrix for 11 proposed projects

Project	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	22.723	5.651	1.902	1.022	1.816	0.661	3.464	6.313	1.010	2.165	3.567
2	5.651	12.166	2.436	2.493	3.322	1.106	2.535	4.619	1.690	0.845	1.392
3	1.902	2.436	1.056	0.587	0.783	0.285	0.622	1.134	0.436	0.156	0.256
4	1.022	2.493	0.587	2.167	3.925	0.292	0.178	0.325	0.267	0.134	0.220
5	1.816	3.322	0.783	3.925	15.389	0.389	0.238	0.433	0.594	0.048	0.078
6	0.661	1.106	0.285	0.292	0.389	0.167	0.247	0.451	0.223	0.074	0.122
7	3.464	2.535	0.622	0.178	0.238	0.247	1.556	2.478	0.378	0.227	0.373
8	6.313	4.619	1.134	0.325	0.433	0.451	2.478	5.167	0.688	0.826	1.361
9	1.010	1.690	0.436	0.267	0.594	0.223	0.378	0.688	0.389	0.182	0.299
10	2.165	0.845	0.156	0.134	0.048	0.074	0.227	0.826	0.182	0.389	0.560
11	3.567	1.392	0.256	0.220	0.078	0.122	0.373	1.361	0.299	0.560	1.056

5.3.2. Scenario 1

In this scenario, the budget constraint is limited to US$200 million.

Objective function: Minimum variance (quadratic function objective)

$$Variance(r) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sigma_{i.j}x_i x_j$$

Subject to the following constraints::

1. $\sum_{i=1}^{n} Budget_i \leq 200$
2. $\sum_{i=1}^{n} Return_i \geq 200$
3. $x_1 + x_2 <= 1$
4. $x_3 = x_1 + x_2$
5. $x_4 = x_1 + x_2$
6. $x_5 = x_1 + x_2$

Using CPLEX, the model was run, and projects 2–5 are selected. The total return is US$221 million, and the budget spent is US$135 million. The risk index is 58.676.

5.3.3. Scenario 2

In this scenario, the budget constraint is strictly set at US$200 million.

Objective function: Minimum variance (quadratic function objective)

$$Variance(r) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sigma_{i.j}x_i x_j$$

Subject to the following constraints:

1. $\sum_{i=1}^{n} Budget_i = 200$

2. $\sum_{i=1}^{n} Return_i \geq 200$

3. $x_1 + x_2 <= 1$

4. $x_3 = x_1 + x_2$

5. $x_4 = x_1 + x_2$

6. $x_5 = x_1 + x_2$

Projects 1 and 3–7 are selected. The total return is US$375 million, and the entire budget is spent. The risk index is 76.857.

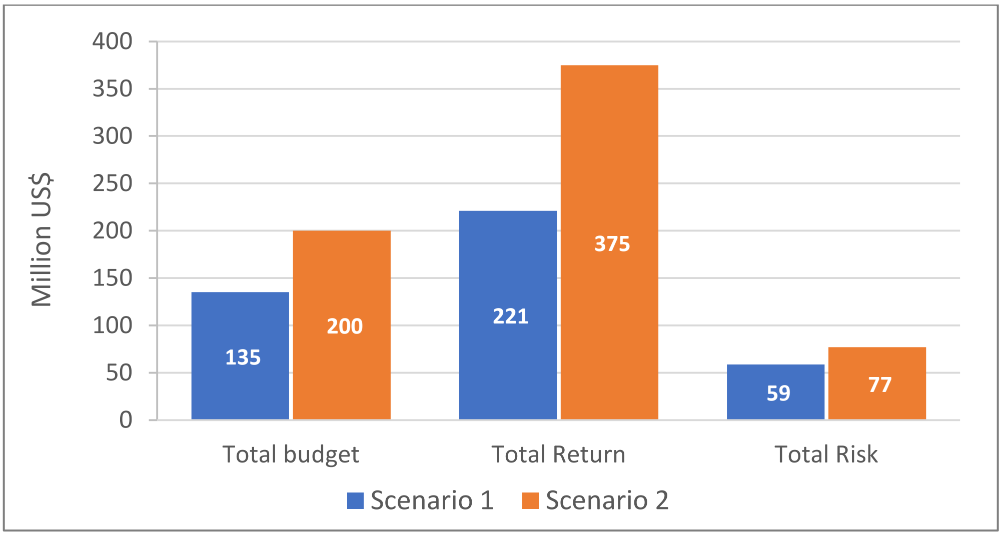


Figure 5-4 Case 2 portfolio optimization using Markowitz Model

5.4. Kataoka's Model

To solve the problem using Kataoka's model, we will assume that the predetermined risk level that the corporation wants to avoid is α= 5%.

Maximize:

$$R_L = \sum_{i=1}^{n} r_i x_i + k_\alpha \sqrt{\sum_{i=1}^{n} {\sigma_i}^2 {x_i}^2}$$

At α= 5%, the value of k_α = –1.645

Subject to:

1. $\sum_{i=1}^{n} Budget_i \leq 200$
2. $\sum_{i=1}^{n} Return_i \geq 200$
3. $x_1 + x_2 <= 1$
4. $x_3 = x_1 + x_2$
5. $x_4 = x_1 + x_2$
6. $x_5 = x_1 + x_2$

Using the exponential solver problem in *BARON*, the optimal project portfolio includes projects 3,4,5,6,7 and 9 and 10. It generates a total return of US$375 million, and the budget spent is US$167million. The risk index is 5.7688 (based on standard deviation). This low risk compared with the results from the Markowitz method is due to the standard deviation being the measure of risk. Each asset's risk is assessed individually without considering the correlations or diversification benefits among assets in a portfolio. Therefore, it does not capture the combined risk effects and potential risk reduction achieved through diversification.

5.5.Discussion of Two Models

Kataoka's model selected seven projects, whereas the Markowitz model selected four (scenario 1) and six projects (scenario 2) (Figure *5-5*). The Markowitz scenario 2, which is forced to use the entire budget, generates a higher risk index than scenario 1. Kataoka's model provides a higher return and ensures a lower risk than Marokowitz scenario 1, which is key information for the decision-maker (Figure *5-6*).

	Projects										
	1	2	3	4	5	6	7	8	9	10	11
Kataoka's model			■	■	■	■	■		■	■	
Markowitz scenario 1		■	■	■	■						
Markowitz scenario 2	■		■	■	■	■	■				

Figure 5-5 Case study 2: Summary of projects selected (in blue)

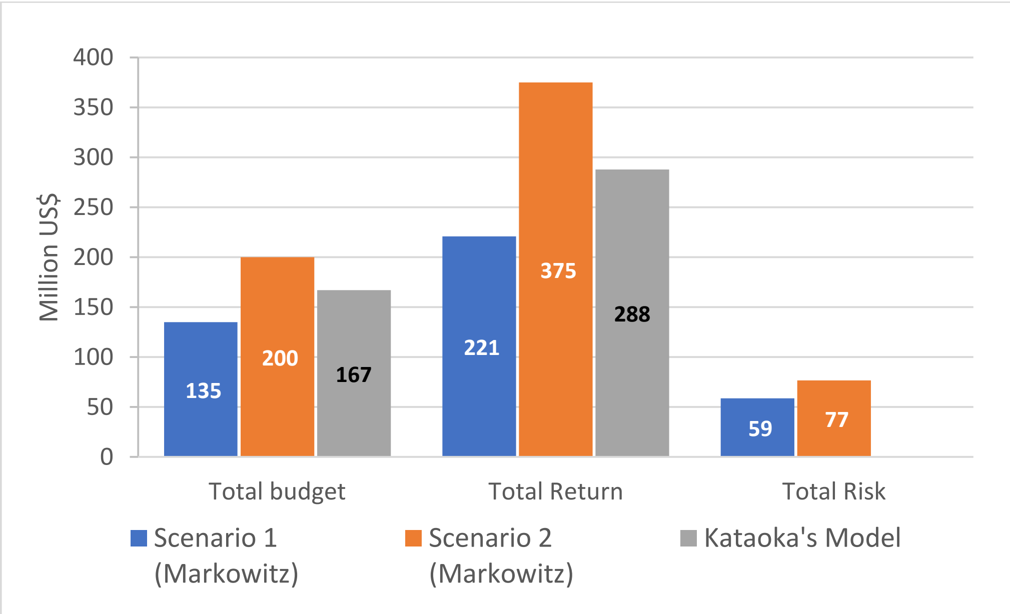


Figure 5-6 Case study 2: Project selection using three models.

6. Case Study 3: UTA for Project Selection in an International Mining Corporation

6.1. Case Study 3 Description

An international mining corporation aims to optimize selection of projects to fund from among 15 proposals submitted by various divisions, including equipment replacement, capacity expansion, additional studies, a new exploration campaign, improvement of current designs, the redesign of a mineral processing plant to increase throughput, new tailings dam construction, and new mine development. The corporation has multiple objectives in project selection, such as attracting new investors; increasing environmental compliance, productivity, and efficiency; and commercial and geographic diversification. The budget is restricted to US$120 million. The corporation should support at least two new projects to sustain long-term growth. Furthermore, it plans to fund at least two projects in Australia and at least one project in Chile based on its strategic direction. The method requires constraints (Table 6–1) and a matrix of scores (Table 6–2). A higher score represents a more profitable feature.

Table 6-1 Project proposals received from divisions of a corporation.

Project	Description	Status	Country	Material	Budget (million US$)	Expected return (million US$)
1	New equipment	Ongoing	Australia	Iron	20	30
2	Social project	Ongoing	Australia	Iron	6	9
3	New tailings dam	Ongoing	Australia	Nickel	7	8
4	Training for workers	Ongoing	Australia	Nickel	1	3
5	New automated equipment	Ongoing	Chile	Copper	24	32
6	More studies	New	Chile	Lithium	15	18
7	Exploration project	New	Peru	gold	8	11
8	New equipment	Ongoing	Peru	Copper	25	30
9	Pipeline construction	Ongoing	Colombia	copper	12	21
10	Exploration project	New	Colombia	Silver	8	16
11	Improvement of design	Ongoing	Mongolia	Copper	4	5
12	Increase in throughput	Ongoing	Canada	Potash	20	26
13	Increase in throughput	Ongoing	Mexico	Copper	12	21
14	New mine project	New	Argentina	Lithium	5	9
15	New mine project	New	Serbia	Lithium	7	16

Table 6-2 Criteria and respective scores for 15 proposed projects

Criteria:	Environment (c_1)	Social (c_2)	Commodity (c_3)	Deposit uncertainty (c_4)	Government (c_5)
Range:	**1–5**	**1–5**	**1–5**	**0–100%**	**1–5**
1	4	4	3	90	5
2	3	5	3	90	5
3	1	2	5	95	5
4	5	5	5	95	5
5	4	3	4	85	4
6	5	3	5	70	4
7	1	2	3	92	2
8	5	2	5	95	2
9	5	3	5	93	4
10	2	3	2	85	4
11	5	5	5	92	3
12	2	5	4	90	5
13	2	2	5	95	3
14	4	2	5	80	2
15	4	2	5	85	2

6.2. Case Study 3 Solution Framework

Figure 6-1 shows the solution process conducted in case study 3. The first step is to interpret the data, including recognizing the different criteria and the constraints. Next the reference set is delimited (Section 3.4). The UTA model can now be applied. Finally, the UTA results are used to assign a weight to each project. Given the associated constraints, a second optimization is established.

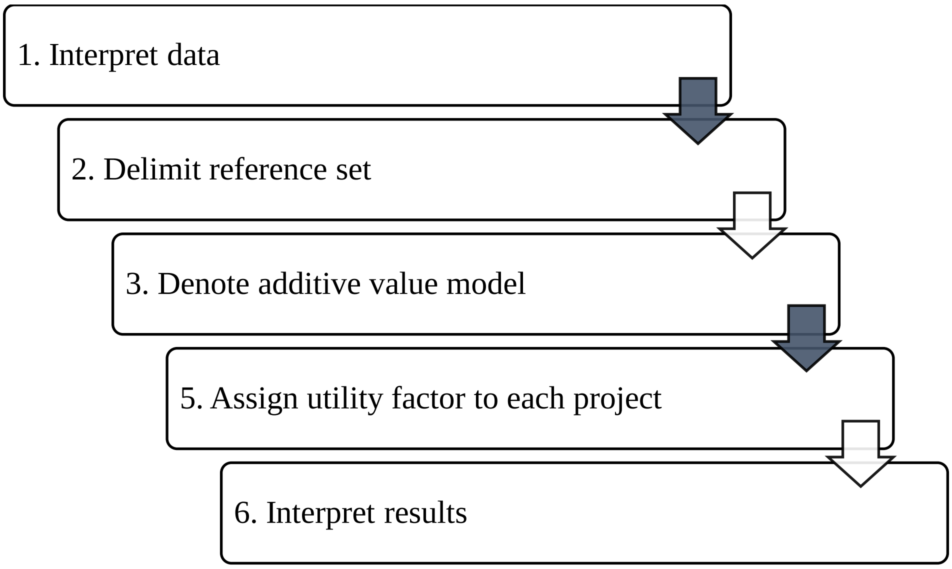


Figure 6-1 Case study 3: Solution process

6.3. UTA method

The criteria score of the 15 projects from Table 6-2 are normalized, as shown in Table 6-3. The reference set of the 15 projects (Table 6-4) is accepted based on the values of $\sum_{i=1}^{n} score(c_{ij})$, where c_i is the ith criteria for project j, and n is the total number of criteria delimited. Next, the threshold $c\ [c_{i(min)}, c_{i(max)}]$ for each criterion is fractionated into equal intervals. The minimum and maximum value of each criterion, the number of intervals, and the interval increment are calculated using Equation 3.12 (Table 6-5). The number of intervals is determined by the decision-maker and is commonly given by the range of data collected from the 15 proposed projects.

Table 6-3 Normalized matrix

Project	**Criteria**				
	c_1	c_2	c_3	c_4	c_5
1	0.75	0.67	0.33	0.80	1.00
2	0.50	1.00	0.33	0.80	1.00
3	0.00	0.00	1.00	1.00	1.00
4	1.00	1.00	1.00	1.00	1.00
5	0.75	0.33	0.67	0.60	0.67
6	1.00	0.33	1.00	0.00	0.67
7	0.00	0.00	0.33	0.88	0.00
8	1.00	0.00	1.00	1.00	0.00
9	1.00	0.33	1.00	0.92	0.67
10	0.25	0.33	0.00	0.60	0.67
11	1.00	1.00	1.00	0.88	0.33
12	0.25	1.00	0.67	0.80	1.00
13	0.25	0.00	1.00	1.00	0.33
14	0.75	0.00	1.00	0.40	0.00
15	0.75	0.00	1.00	0.60	0.00

Table 6-4 Reference set of 15 alternatives

Reference order	Project	Total score $\sum_{i=1}^{n} score(c_{ij})$
1	4	5.0
2	11	4.2
3	9	3.9
4	12	3.7
5	2	3.6
6	1	3.6
7	5	3.0
8	3	3.0
9	8	3.0
10	6	3.0
11	13	2.6
12	15	2.4
13	14	2.2
14	10	1.9
15	7	1.2

Table 6-5 Minimum and maximum value of each criterion and proposed intervals

	Criteria				
	c_1	c_2	c_3	c_4	c_5
Minimum	1	2	2	0.7	2
Maximum	5	5	5	0.95	5
No. intervals	4	3	3	4	3
Increment	0.25	0.33	0.33	0.25	0.33

The partial utilities, u, calculated for each project (Equation 3.13) are listed in **¡Error! No se encuentra el origen de la referencia.** for criterion 1, $u_1(c_i(a_t))$, where i is the interval, and alternative a_t is the project t, which is between 1 and 15. Criterion 1 is divided into five intervals based on the score (Table *6-4*). The partial utility for each project falls in a particular interval.

Table 6-6 Partial utility values for criterion 1

Interval:	**1**	**2**	**3**	**4**	**5**
Project	$u_1(c_1(a_t))$	$u_1(c_2(a_t))$	$u_1(c_3(a_t))$	$u_1(c_4(a_t))$	$u_1(c_5(a_t))$
1	0.00	0.00	0.00	**1.00**	0.00
2	0.00	0.00	**1.00**	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	**1.00**
5	0.00	0.00	0.00	**1.00**	0.00
6	0.00	0.00	0.00	0.00	**1.00**
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	**1.00**
9	0.00	0.00	0.00	0.00	**1.00**
10	0.00	**1.00**	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	**1.00**
12	0.00	**1.00**	0.00	0.00	0.00
13	0.00	**1.00**	0.00	0.00	0.00
14	0.00	0.00	0.00	**1.00**	0.00
15	0.00	0.00	0.00	**1.00**	0.00

Next, the utility value is found for each alternative using Equation 6.1:

$$U[c(a)] = \sum_{i=1}^{n} u_i(c_i(a)) - \sigma^+ + \sigma^- \quad \forall a \in A \tag{6.1}$$

Where, $\sigma^+$and σ^- are the positive and negative potential error related to $U[c(a)]$.

Equation 6.2 shows the utility value for project 1 (new equipment). The same steps are followed for the other 14 proposed projects.

$$U[c(a_1)] = 1 * u_1\big(c_4(a_1)\big) + 1 * u_2\big(c_3(a_1)\big) + 1 * u_3\big(c_2(a_1)\big) + 0.8 * u_4\big(c_4(a_1)\big) + 0.2 * u_4\big(c_5(a_1)\big) + 1 * u_5(c_4(a_1)) - \sigma^+ + \sigma^- \tag{6.2}$$

Subject to the set of reference described in Table *6-4*, the sequential actions are defined, where δ is a small number which assure the positive difference between each pare of projects in the reference set using Equation 3.17.

$$\Delta(a_4, a_{11}) \geq \delta,\ \Delta(a_{11}, a_9) \geq \delta,\ \Delta(a_9, a_{12}) \geq \delta,\ (a_{12}, a_2) \geq \delta$$

$$\Delta(a_2, a_1) \geq \delta,\ \Delta(a_1, a_5) \geq \delta,\ \Delta(a_5, a_3) \geq \delta,\ \Delta(a_3, a_8) \geq \delta$$

$$\Delta(a_8, a_6) \geq \delta,\ \Delta(a_6, a_{13}) \geq \delta,\ \Delta(a_{13}, a_{15}) \geq \delta,\ \Delta(a_{15}, a_{14}) \geq \delta$$

$$\Delta(a_{14}, a_{10}) \geq \delta,\ \Delta(a_{10}, a_7) \geq \delta$$

The objective function is to minimize the sum of errors using Equation 6.3:

$$\sum_{k=1}^{n}(\sigma^{+}(a_k)+\sigma^{-}(a_k)) \tag{6.3}$$

Subject to:

$$\Delta(a_4, a_{11}) \geq \delta,\ \Delta(a_{11}, a_9) \geq \delta,\ \Delta(a_9, a_{12}) \geq \delta,\ (a_{12}, a_2) \geq \delta$$

$$\Delta(a_2, a_1) \geq \delta,\ \Delta(a_1, a_5) \geq \delta,\ \Delta(a_5, a_3) \geq \delta,\ \Delta(a_3, a_8) \geq \delta$$

$$\Delta(a_8, a_6) \geq \delta,\ \Delta(a_6, a_{13}) \geq \delta,\ \Delta(a_{13}, a_{15}) \geq \delta,\ \Delta(a_{15}, a_{14}) \geq \delta$$

$$\Delta(a_{14}, a_{10}) \geq \delta,\ \Delta(a_{10}, a_7) \geq \delta$$

$$\textstyle\sum_{i=1}^{n}\sum_{j=1}^{a_i-1} u_1(c_i(a_t)) = 1,\ u_1(c_i(a_t)) \geq 0\ ,\ \ \sigma^{+}(a_t) \geq 0\ \sigma^{-}(a_t) \geq 0$$

Where, a_t represents project *t*, which can take a value from 1 to 15.

6.3.1. UTA Solution

Using IBM® ILOG® CPLEX® Optimization Studio (IBM, Armonk, NY) software, the linear programming model given above is solved to minimize errors associated with the utility of each project (Table 6-7). The next step is to calculate a weighting value for each project by dividing the sum of the all project utilities between the individual project utility. These weights are applied to optimize the return and apply the constraints established in Section 6.1.

Table 6-7 Project utility calculated with the utility additive method and weighting applied.

Project	Project Utility	Weight (%)
4	1.000	13.1
11	0.898	11.8
9	0.566	7.4
12	0.556	7.3
2	0.546	7.2
1	0.536	7.0
5	0.526	6.9
3	0.516	6.8
6	0.501	6.6
8	0.491	6.5
13	0.442	5.8
15	0.432	5.7
14	0.422	5.5
10	0.119	1.6
7	0.056	0.7
Total	**7.607**	**100**

6.3.2. Maximizing Return and Application of Portfolio Constraints

After the UTA model is applied, a linear programming model is developed to select the projects that maximize the return (objective function) and respect the constraints.

Objective function:

$$Return\ (r) = \sum_{i=1}^{n} w_i * r_i x_i$$

$$x_i = \begin{cases} 1\ if\ project\ i\ is\ selected \\ otherwise\ is\ 0 \end{cases}$$

Where w_i is the weight from Table 6-7.

Constraints:

- Budget should be less than US$120 million.

$$\sum_{i=1}^{n} b_i = 120$$

- At least two new projects must be approved to ensure a long-term portfolio.

$$x_1 + x_2 + x_3 + x_4 \leq 2$$

- At least one project should be developed in Chile.

$$x_5 + x_6 = 1$$

- At maximum, two projects should be accepted for Australia.

$$x_6 + x_7 + x_{10} + x_{14} + x_{15} \geq 2$$

Using CPLEX Optimization software, the following projects are selected: 1, 2, 5, 7, 8, 9, 10, 11, and 13. The total return is US$175 million.

6.4. Case Study 3 Results

Projects 1, 5, and 8 had the highest expected returns and are selected (Figure *6-2*). Projects 2 and 7 with the lowest expected returns are also selected because of the weights applied and the constraints involved. The top projects in the reference set are projects 4, 11, and 9. After optimization, only project 9 is chosen; the others are excluded due to low expected returns.

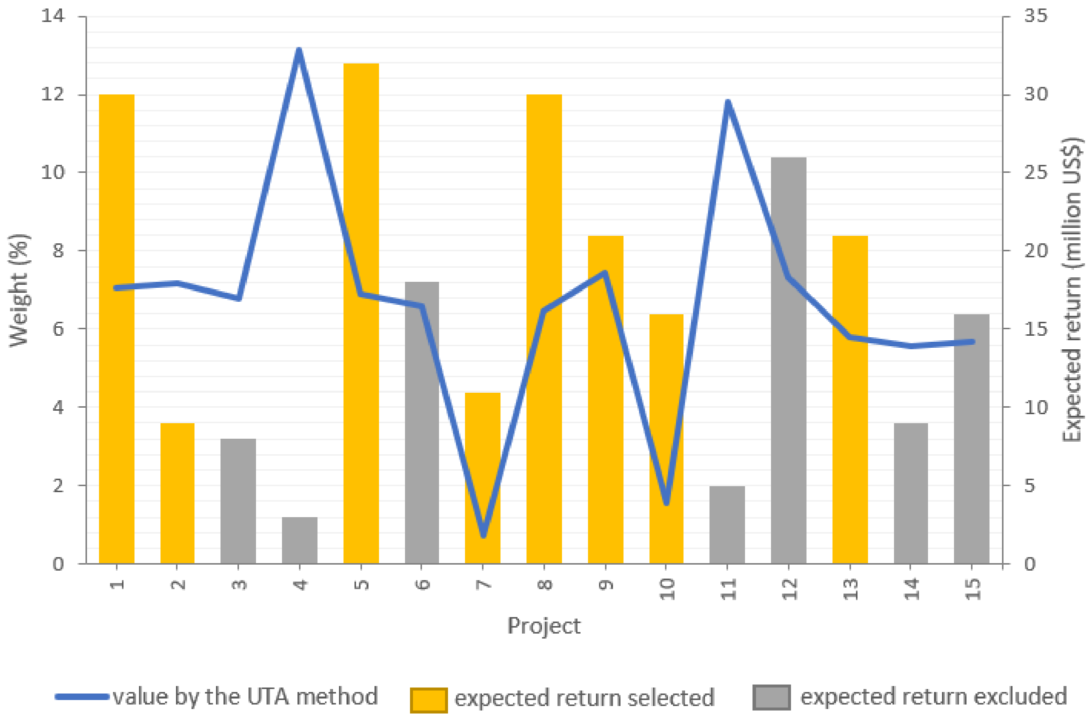


Figure 6-2 Case study 3: Utility additive method method results; yellow and grey bars show projects selected and excluded after the optimization, respectively

7. Conclusions and Future Work

Mining corporations must continuously adapt their strategies to market needs. Project portfolio management is a vital process that allows corporations to align their strategies with the multiple risks that exist and market values. The literature provides many models to accomplish this, depending on corporate objectives. However, the utility of these models is limited. This thesis aims to show how project portfolio techniques can be applied to help mining corporations minimize risk and improve decision-making to ensure continuous growth.

This thesis outlined three approaches to solving PPM through case studies. Case study 1 focuses on an annual sales strategy containing four sales options: spot, future, swap, and auction markets. The Markowitz model minimizes risk while ensuring the required returns. Kataoka's model creates a trade-off between mean and variance, which is achieved by a factor based on a prespecified reliability level. Case study 2 uses Markowitz and Kataoka's models to select projects from those proposed by the geography-based or commodity-based divisions of the mining corporation. Two risk-based methods were tested: strict and maximum allowable budget constraint. These techniques can be seen as risk diversification approaches. Case study 3 uses an MCDM technique to select a project portfolio, which allows decision-makers to consider multiple objectives. The UTA used allows decision-makers to incorporate their reference set depending on the corporate strategy.

Future work should deal with making subjective estimates (i.e., based on the professional judgement of the decision-maker) into objective ones: the objective function coefficients and constraints and the covariance matrix for the Markowitz and Kataoka's models and the decision-maker's set of reference and choice of intervals for the UTA. Further, other

MCDM methods could be used to benchmark the results of the three approaches evaluated here. Also, including sensitivity analysis is can improve decision-making in project portfolio management.

8. References

Archer, N., & Ghasemzadeh, F. (1999). An integrated framework for project portfolio selection. International Journal of Project Management, 207-216.

Balci, M., & Kumral, M. (2022). Building an innovation strategy and culture on the structural characteristics. Resources Policy, 102936.

Beuthe, M., & Scannella, G. (2001). Comparative analysis of UTA multicriteria methods. European Journal of Operational Research 130, 246-262.

BHP Corporation. (2021). BHP Annual Report 2021. BHP Corporation. https://www.bhp.com/investors/annual-reporting/annual-report-2021.

Bissoondoyal-Bheenick, E., Brooks, R., & Xuan Do, H. (2023). ESG and firm performance: The role of size and media channels. Economic Modelling, 106203.

Casterline, S. D., & Yetman Jr., R. G. (2010). Chapter 9 Portfolio Management Applications. In S. D. Casterline, & R. G. Jr., Investor's Passport to Hedge Fund Profits: Unique Investment Strategies for Today's Global Capital Markets (pp. 305-329). John Wiley & Sons, Inc.

Cernauskas, D. (2011). Volatility, Risk Aversion, and Portfolio Management. In A. T. Cernauskas, Essentials of Risk Management in Finance (pp. 192-213).

Cooper, R., Edgett, S., & Kleinschmidt, E. (2001). Portfolio Management for new product development: results of an industry practices study. R&D Management, 361-380.

Deloitte. (2018). Commodity Price Risk Management A manual of hedging commodity price risk for corporates. MCX Metal&Energy .

Doumpos, M., & Zopounidis, C. (2004). Multicriteria Decision Aid Classification Methods. New York, Boston, Dordrecht, London, Moscow: Kluwer Academic Publishers.

Dries Faems, B. V. (2005). Interorganizational Collaboration and Innovation: Toward a Portfolio Approach. Product Innovation Management, 238-250.

Edgett, S. J. (2010). Portfolio Management. Retrieved from Wiley International Encyclopedia of Marketing (eds J. Sheth and N. Malhotra): https://doi-org.proxy3.library.mcgill.ca/10.1002/9781444316568.wiem05006

Enoch, C. N. (2019). Project Portfolio Management, Second Edition : A Model for Improved Decision Making. Business Expert Press.

Francis, J. C., & Kim, D. (2013). Modern Portfolio Theory: Foundations, Analysis, and New Developments, + Website. John Wiley & Sons, Inc.

G. Smith, L. B. (2018). Incorporation of the socio-cultural dimension into strategic long-term planning of mineral assets in South Africa. Journal of The South African Institute of Mining and Metallurgy, 331-336.

Gama Lopes, Y., & Teixeira de Almeida, A. (2015). Assessment of synergies for selecting a project portfolio in the petroleum industry based on a multi-attribute utility function. Journal of Petroleum Science and Engineering, 131-140.

Görner, S., Kudar, G., Mori, L., Reiter, S., & Samek, R. (2020). The mine-to-market value chain: A hidden gem. McKinsey's Global Energy & Materials Practice.

Illmer, S. J., & Senik, D. A. (2013). Performance Evaluation: An Introduction. Retrieved from CFA Institute: https://www.cfainstitute.org/-/media/documents/support/programs/cipm/2019-cipm-l1v1r3.ashx#:~:text=In%20the%20investment%20management%20industry,investment%20portfolios%20over%20specified%20periods.

Inuiguchi, M., & Ramik, J. (1998). Possibilistic linear programming: a brief review of fuzzy mathematical programming and a comparison with stochastic programming in portfolio selection problem. Elsevier.

Jones, O., Lilford, E., Spearing, A., & Taylor, G. (2019). The Business of Mining. The Mining Business, Uncertainty, Project Variables and Risk, Royalty Agreements, Pricing and Contract Systems, and Accounting for the Extractive Industry. Leiden, The Netherlands: Curtin University.

Jones, O., Lilford, E., Spearing, A., & Taylor, G. (2019). The mining business, uncertainty, project variables and risk, royalty agreements, pricing and contract systems, and accounting for the extractive industry. Leiden, The Netherlands: CRC Press/Balkema.

Lindsay Delevingne, W. G. (2020, January). Climate risk and decarbonization: What every mining CEO needs to know. McKinsey&Company.

Markowitz, H. M. (1971). Portfolio Selection : Efficient Diversification of Investments. Yale University Press.

Mathur, S. (2006). Project portfolio management techniques. PMI® Global Congress 2006—Asia Pacific, Bangkok, Thailand. Newtown Square: PA: Project Management Institute.

Meskendahl, S. (2010). The influence of business strategy on project portfolio management and its success - A conceptual framework. International Journal of Project Management, 807-817.

Monks, R. A., & Minow, N. (2012). Corporate Governance,5th edn. John Wiley & Sons.

Montibeller, G., & Franco, A. (2010). Multi-Criteria Decision Analysis for Strategic. In C. Z. Pardalos, Handbook of Multicriteria Analysis (pp. 25-50). Springer-Verlag Berlin Heidelberg.

Njike, A. N., & Kumral, M. (2019). Mining corporate portfolio optimization model with company's operational performance level and international risk. Mineral Economics, 307–315.

Oltmann, J. (2008). Project portfolio management: how to do the right projects at the right time. Paper presented at PMI® Global Congress 2008—North America, . Denver, CO. Newtown Square: Newtown Square, PA: Project Management Institute.

Ozcer, P. (2021). Week 8: Multi criteria Decision Analysis (MCDA) . Course SEAD 550 Decision Making for Sustainability in Engineering and Design. Montreal, Quebec, Canada: McGill University.

Priolon, J. (2019). Financial Markets for Commodities. Wiley-ISTE.

Qing, X., Zhen, W., Sijing, L., & Dong, Z. (2014). An improved portfolio optimization model for oil and gas investment selection. Petroleum Science , 181-188.

Ramírez-Orellana, A., Martínez-Victoria, M., García-Amate, A., & Rojo-Ramírez, A. A. (2023). Is the corporate financial strategy in the oil and gas sector affected by ESG dimensions? Resources Policy, 103303.

Renaud, M., & Kumral, M. (2021). Out of the Comfort Zone: Quantifying Country Risk for Foreign Mining Project Investment Feasibilities. Mining, Metallurgy & Exploration , 2323–2335.

Rio Tinto Corporation. (2022). Annual Report 2021. Rio Tinto Company. https://www.riotinto.com/invest/reports/annual-report.

Scott, D. W., Frasera, J., Reynoldsc, A., & Kunza, N. C. (2020). Mining needs new business models. The Extractive Industries and Society, 263-266.

Seeger, M. (2019). Mining capital. Methods, best practices and case studies for financing mining projects. Switzerland: Springer Nature.

Smith, G., & Brooks, L. (2018). Incorporation of the socio-cultural dimension into strategic long-term planning of mineral assets in South Africa. Journal of The South African Institute of Mining and Metallurgy, 331-336.

Smith, G., Pearson-Taylor, J., Anderson, D., & Marsh, A. (2007). Project valuation, capital investment and strategic alignment—tools and techniques at Anglo Platinum. The Journal of The Southern African Institute of Mining and Metallurgy, 67-74.

Steuer, R. E., & Na, P. (2003). Multiple criteria decision making combined with finance: A categorized bibliographic study. European Journal of Operational Research 150 , 496-515.

Swensen, D. F. (2000). Pioneering Portfolio Management. New York: Free Press.

Teck Corporation. (2022). 2021 Annual Report. Teck mining company. https://www.teck.com/investors/financial-reports/annual-reports-archive/.

The Enterprise Portfolio Management Council. (2009). Project portfolio management : a view from the management trenches. Newtown Square, PA: Wiley.

Warren, G. J. (2019). Choosing and Using Utility Functions in Forming Portfolios. Financial Analysts Journal, 39-69.

Wu, T., & Chatzipanos, P. (2018). Implementing Project Portfolio Management. Atlanta: Project Management Institute, Inc.

Wulandari, F., & Drozdovica, J. (2022, June). Gold price predictions for next years. Retrieved from Capital.com: https://capital.com/gold-price-forecast-next-5-years

Yaschenko, S., Polyakov, V., & Sabitova, T. (2021). Organizational structures of mining companies: composition and development. SHS Web of Conferences 106. Volgograd, Russia.